Integration of Hardware-in-the-loop Facilities Over the Internet

Hardware-in-the-loop User Group Meeting
April 15, 2009

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Mark J. Brudnak, Ph.D., U.S. Army RDECOM-TARDEC
Wilford Smith, SAIC
Jarrett Goodell, SAIC

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
15 APR 2009	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Integration of Hardware-in-the-loop Facilities Over the Internet	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Mark J. Brudnak; Wilford Smith; Jarrett Goodell	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000	**19796RC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	TACOM/TARDEC
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	19796RC

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

Presented at the Hardware-in-the-loop User Group Meeting, 15 APR 2009, Wright Patterson AFB, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

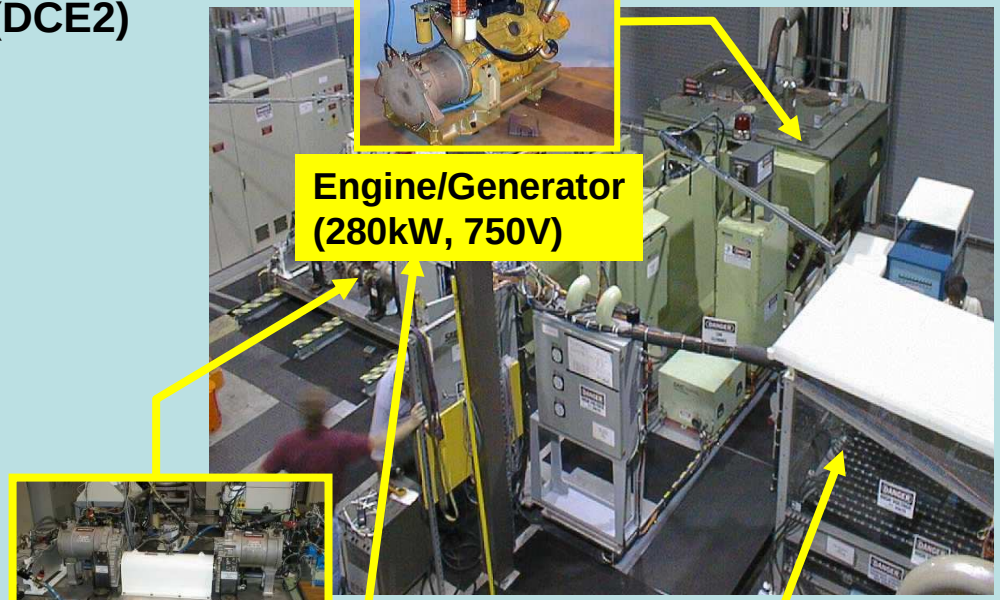
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**57**	

Power & Energy SIL

P&E SIL

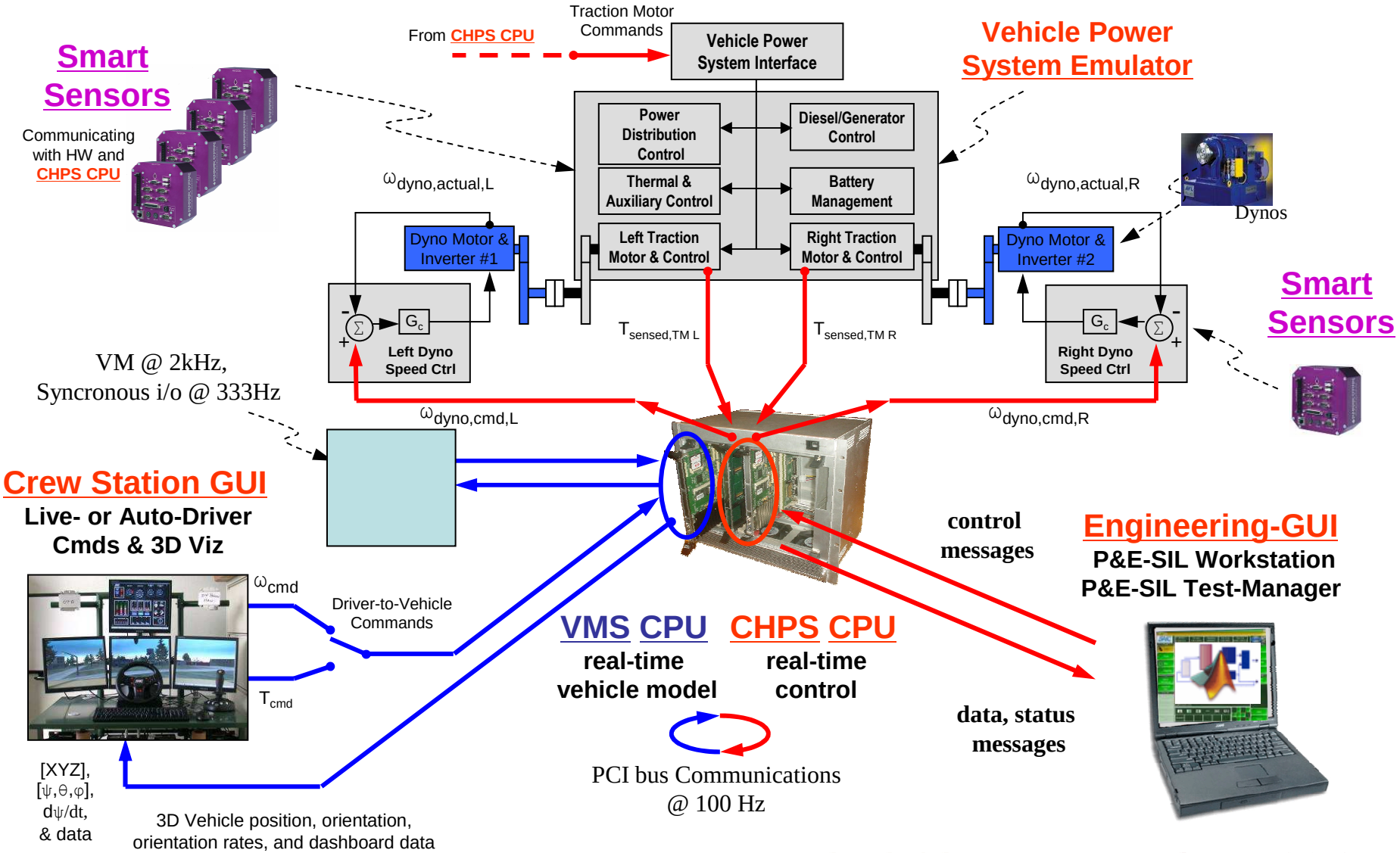
- Series Hybrid-electric power system
- Laboratory based evaluation of design alternatives
- Driven by automated controller
- Requires a-priori duty cycle

Lumpy (DCE2)

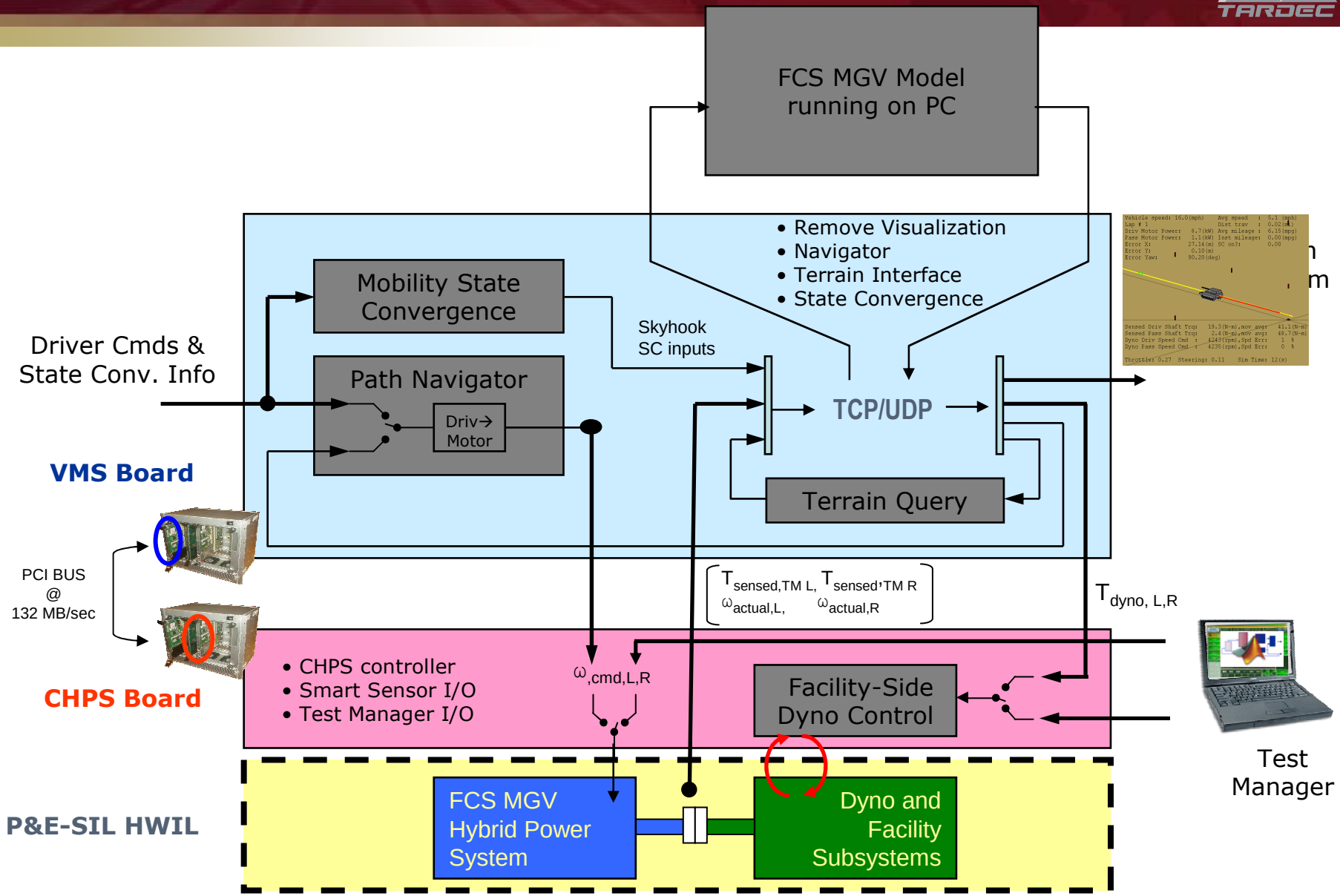


Hermit (DCE3)

SIL HWIL and Driver-in-the-Loop Layout

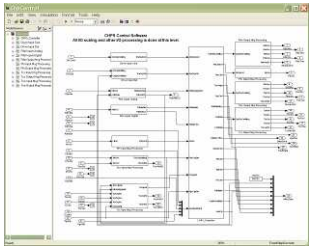


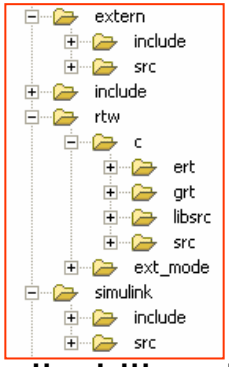
P&E-SIL Architecture



P&E-SIL – Automation of Code Generation and Integration

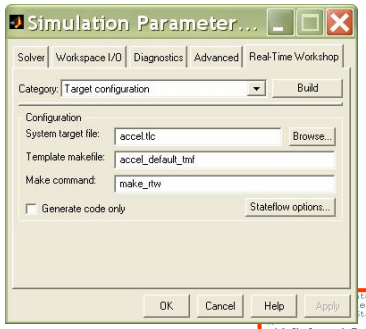
Graphical code





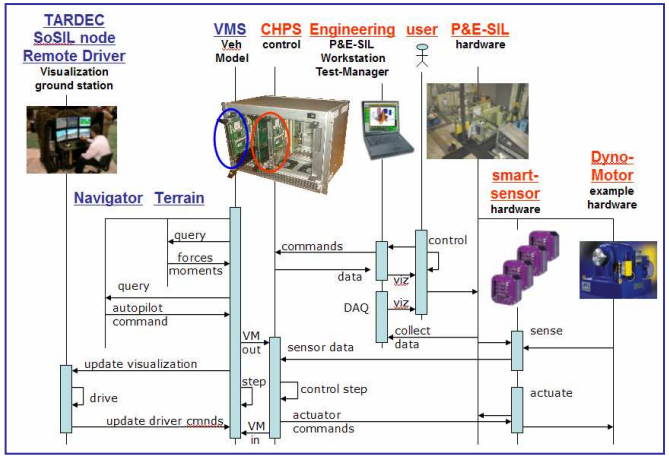
compiled libraries

Conversion to Real-time



Embedded C/C++ code

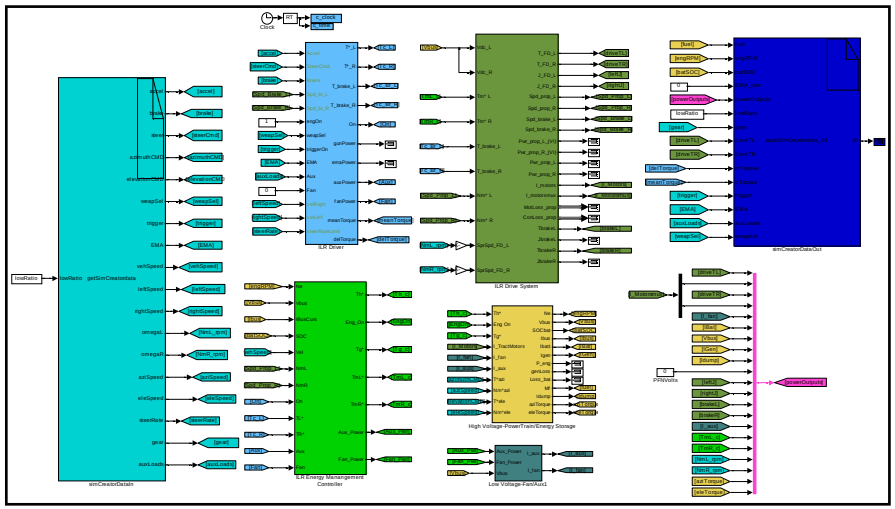
embedded hardware



OS-interface code

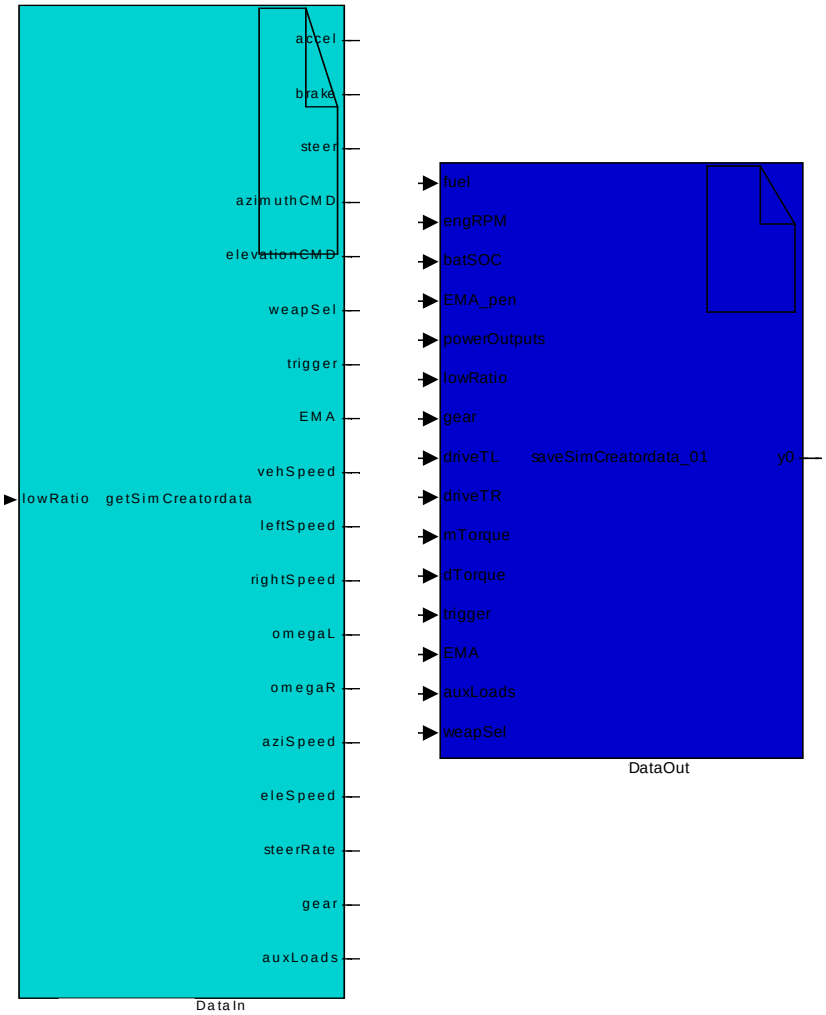
Simulation Design – Power System

- Model: GVSL
  - Assumptions: SS torque transfer in gear train,
  - Current Power Systems: 420kW Engine, 410kW Generator, 500kW Battery (consistent with 24-ton FCS-like vehicle)
- Blocks:
  - Input
    - *Inputs from the Vehicle*
  - Output
    - *Outputs to the Vehicle*
  - High Voltage Powertrain & Energy Storage
    - *CHPSPerf- Engine, Generator, & Battery*
    - *420kW Turbo-Diesel Engine/ 410kWGenerator*
    - *Li-Ion Battery direct connected to 510V Bus*
    - *Dump Resistor*
    - *Turret Azimuth & Gun Elevation Motors*
  - Drive System
    - *Independent Left/Right Motors (ILR), transmission, & brakes*
    - *Gears include Coulombic, Viscous, and Mesh gear losses*
  - Energy Management
    - *Power Generation and Motor controllers (translates commanded torques to machine torques)*
  - Driver
    - *Speed-based mobility control (throttle/steer commands to torque commands) for low vehicle speeds*
    - *Torque-based mobility control for high vehicle speeds*
    - *Blended mobility control for mid vehicle speeds*
  - Low Voltage (Fan/Aux)
- Input File *gvsl_Input.m* defines input parameters



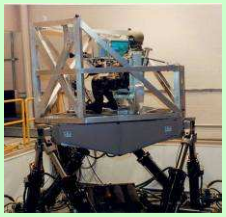
Simulation Design: Power System/SimCreator Interface

- Links with shared workspace with the vehicle module
- Input Block:
  - Commands/States from vehicle model: *accel, brake, steer, gun azimuth/elevation, gun trigger, EMA, speeds/rates (vehicle, track, sprocket, turret azimuth/elevation, steer), gear, aux. loads*
  - Includes speed sign management for neutral and reverse
- Output Block:
  - Power outputs (*propulsion & turret motor torques, sprocket & brake torques, mean & delta torque, fan/battery current & voltage, generator & dump resistor current, PFN voltage, Aux system current*), fuel, engine speed, battery SOC, EMA/gun readiness, Left & Right MOIs, gear.
  - Includes torque sign management for neutral and reverse



RemoteLink Internet ICD, v1.11

GVSL Warren MI



VehModelFaults > 0 for Inf or NaN trapped on inputs/outputs, max speed or Euler angle exceeded

udp ports 5100, 5101

udp ports 5115, 5116

GVSL_out

52 floats, 208 bytes

Net QOS	38		sim_time_gvsl (s)
	39		sim_time_sil (s)
	40		round trip delay gvsl (s)
	41		round trip delay sil (s)
	42		GVSL_out update rate at SIL (Hz)
	43		SIL_out update rate at GVSL (Hz)
Health Status	50		Veh_dynamics_up (0/1)
	51		Power_system_SC_up (0/1)
	52		ESS_up (0/1)

SIL_out

104 floats, 116 bytes

Net QOS	87		sim_time_gvsl (s)
	88		sim_time_sil (s)
	89		round trip delay gvsl (s)
	90		round trip delay sil (s)
	91		GVSL_out update rate at SIL (Hz)
	92		SIL_out update rate at GVSL (Hz)
Health Status	102		VMS/veh dyn Status (0/1)
	103		HWIL Status (0/1)
	104		SC Status (0/1)

Initiate SIL HW shutdown if any below are TRUE:

- `GVSL_Veh_Dyn_up == 0`
- `GVSL_Pwr_Sys_SC_up == 0`
- `GVSL_ESS_up == 0`
- `Net_data_delay > 10s == 1`

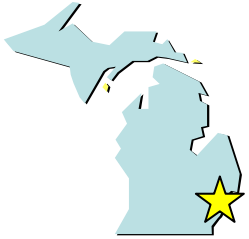
SIL San Jose Ca

Signal SIL HW health with:

- `SIL_Veh_Dyn_Faults == 0`
- `SIL_HWIL_Faults == 0`
- `SIL_SC_Faults == 0`

Motion Base Simulators

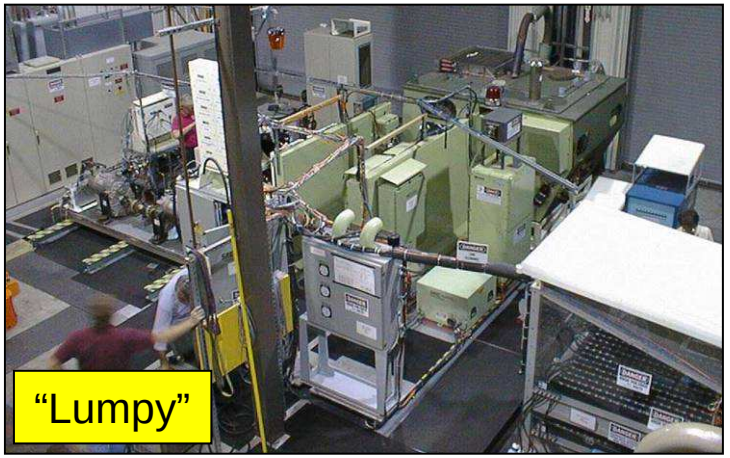
- Man-rated motion base simulator
- Integrated immersive simulation environment
- Real-time vehicle model
- Integrated CAT Crewstation
- Ideal facility for capturing soldier behavior (i.e. duty cycles)

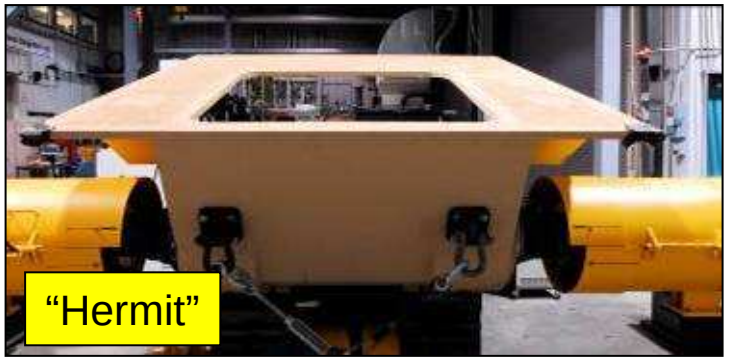


TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Duty Cycle Motivation

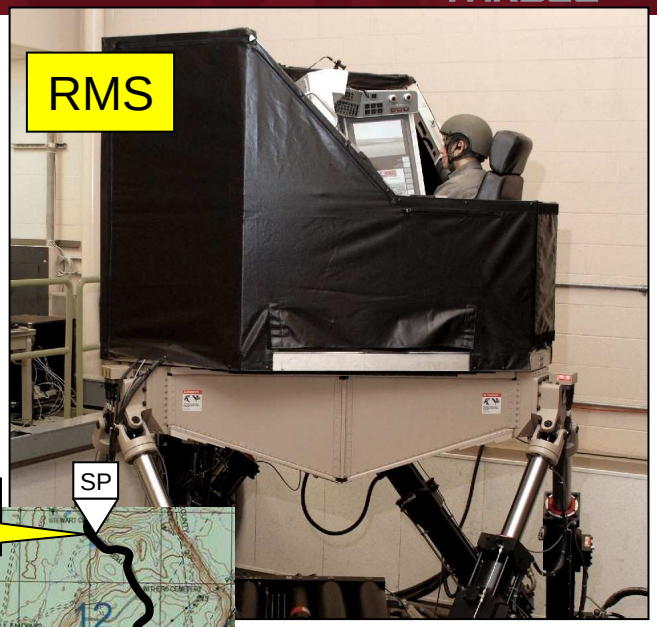
- The Power & Energy SIL in Santa Clara, CA.
  - Series hybrid electric power system
  - Mobility loads:
    - Traction drive motors
  - Non-mobility loads:
    - Constant on/off loads
    - Time varying loads
    - Pulse power loads
- Non-mobility and mobility loads need to share the available power.
- What is the impact of power management choices?
- How should components be sized?
- Simple drive cycles were inadequate.
- → Need a relevant *Duty Cycle*

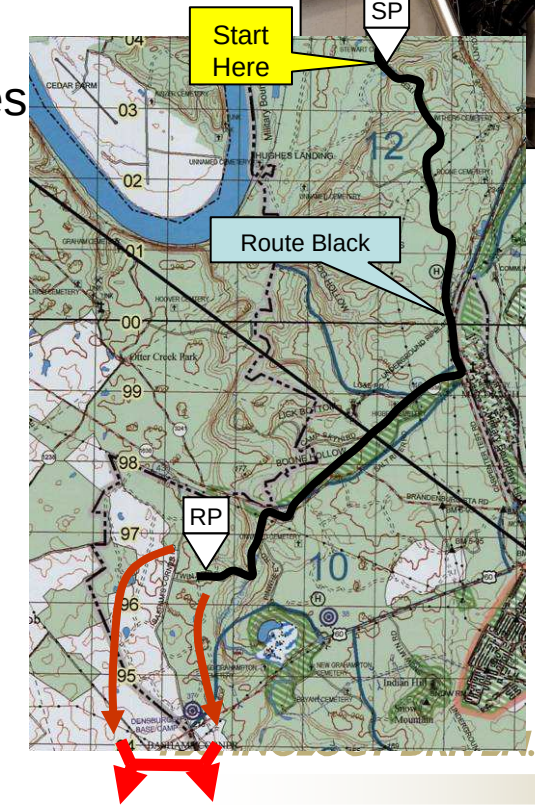




Duty Cycle Experiment 2

- 12 trained Army driver/gunner subjects
- 13 km route
- Avg 42 minutes driving
- Grades greater than 30%
- 7 engagements with OneSAF opposition force infantry and vehicles





Historical Survey

- Duty Cycle Experiment 2 (DCE2): June 2006


Driver/Gunner/Chassis (TARDEC)

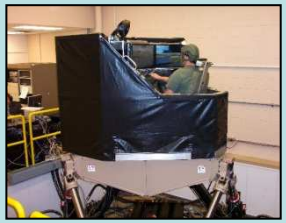
Power Train (SIL)

- Duty Cycle Experiment 3 (DCE3): June 2007


Driver/Gunner/Chassis (TARDEC)

Power Train (SIL)

- ILIR: FY08

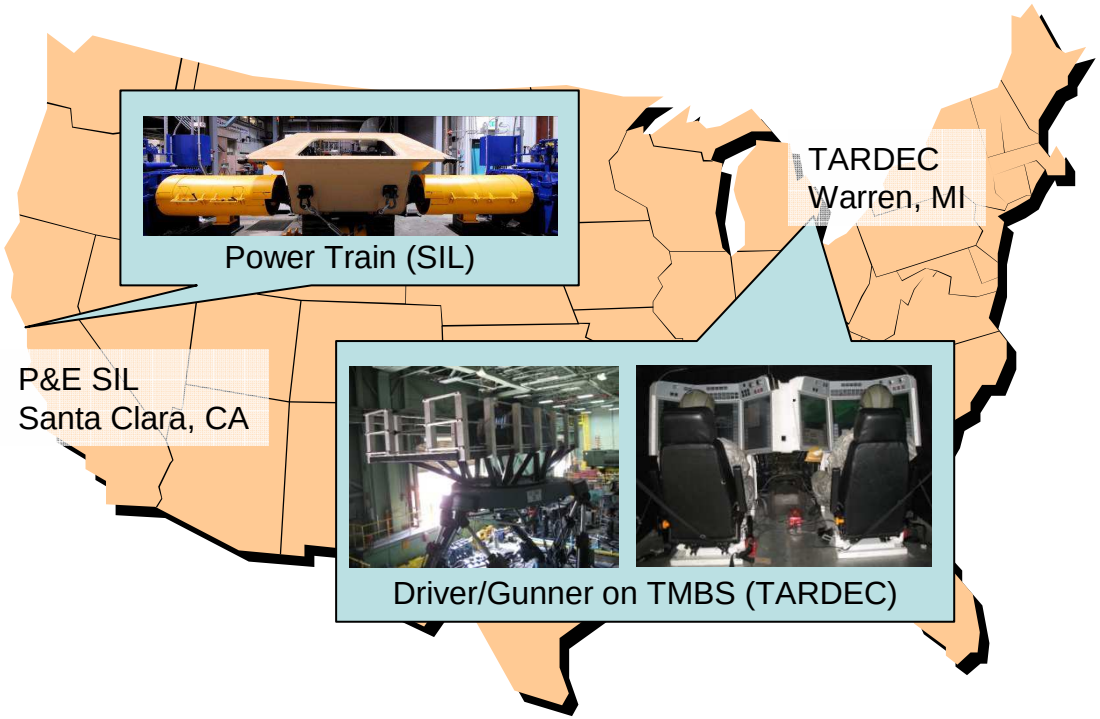



Driver/Gunner/Chassis (TARDEC)

Engine (Ann Arbor, MI)

Long Haul Motivation

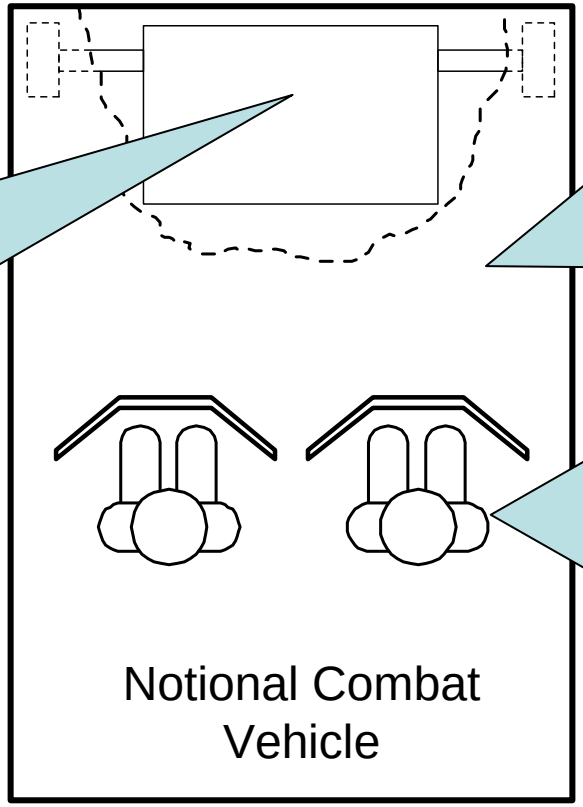
- Geographically disbursed.
- High-fidelity.
- Integration improves fidelity of experiments.
- Dynamical systems, the RMS and P&E SIL like tight loops. Substantial delays introduce instabilities.



2,450 Miles by Roads
2,080 Miles by Direct Route

Concept

Power Train (SIL)



Notional Combat Vehicle

Vehicle Dynamics and Terrain (TARDEC)

Driver/Gunner (TARDEC)

- Remote location of power system is transparent to the operators.

Interconnections

Driver/Gunner (TSL)

Motion

Sprocket Speeds

Vehicle Dynamics and Terrain

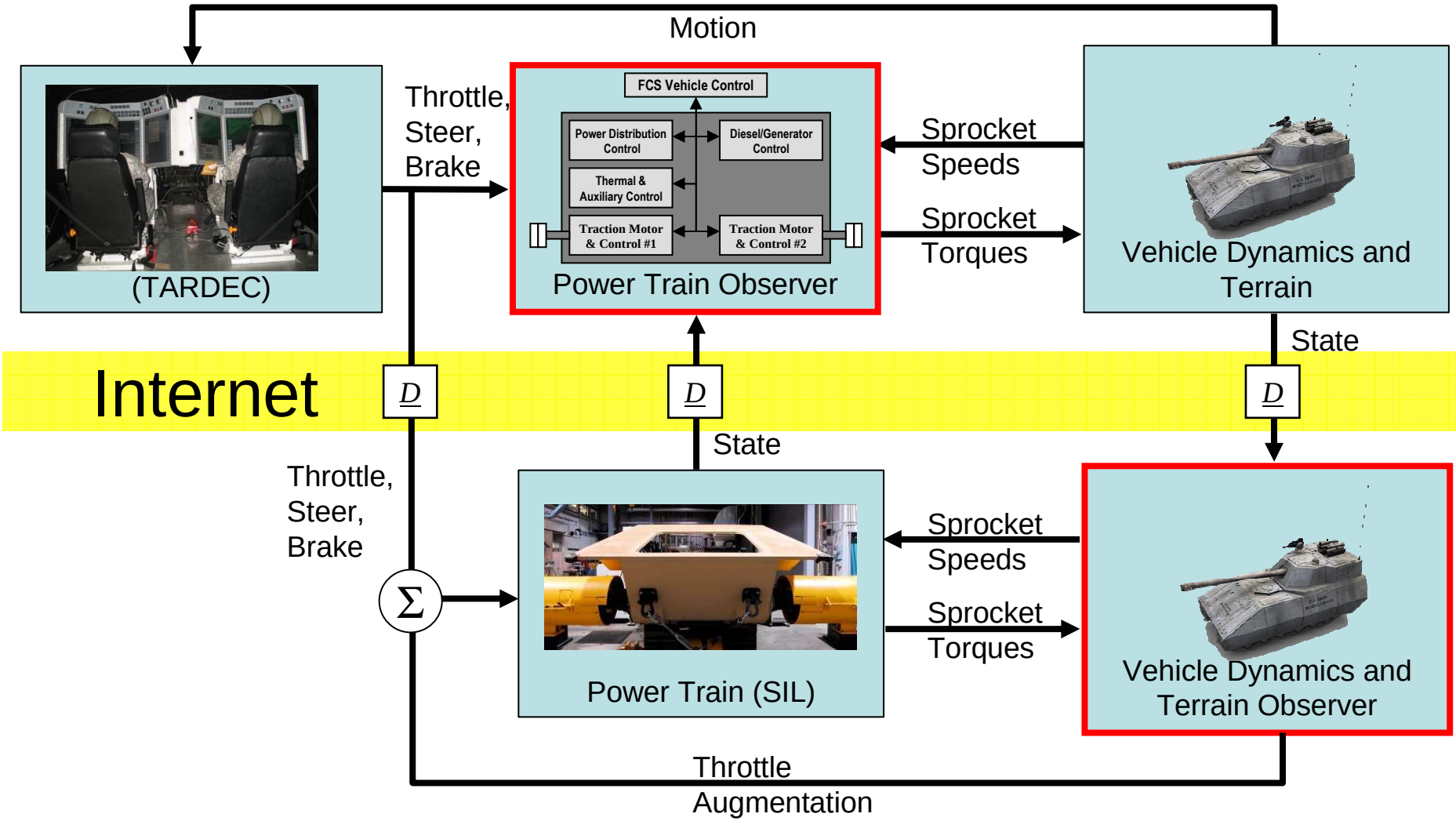
Communication Channel

Throttle, Steer, Brake

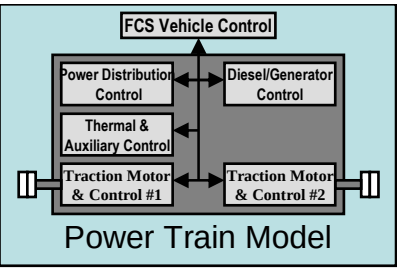
Power Train (SIL)

Sprocket Torques

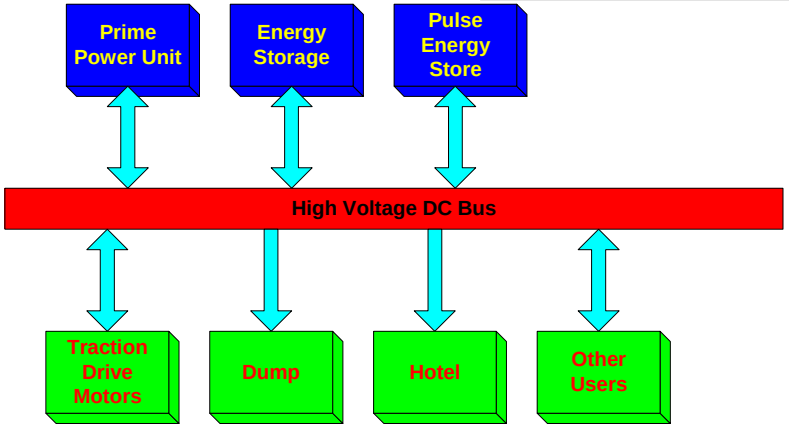
End Design

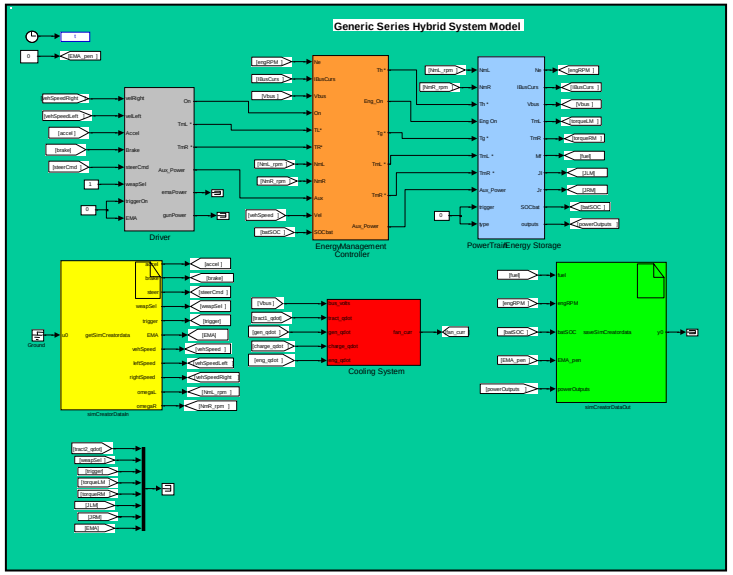

Motion
(TARDEC)
Throttle,
Steer,
Brake
FCS Vehicle Control
Power Distribution Control
Diesel/Generator Control
Thermal & Auxiliary Control
Traction Motor & Control #1
Traction Motor & Control #2
Power Train Observer
Sprocket Speeds
Sprocket Torques
Vehicle Dynamics and Terrain
State
Internet
D
D
D
State
Throttle,
Steer,
Brake
Σ
Power Train (SIL)
Sprocket Speeds
Sprocket Torques
Vehicle Dynamics and Terrain Observer
Throttle Augmentation

Power System Model



- Series Hybrid Power System for MCS
- Independent Left/Right
- Diesel Engine/Generator
- 600 V bus w/Battery
- Two 300kW traction motors.
- Includes thermal model
- Implemented in graphical modeling tool and converted to real-time code.

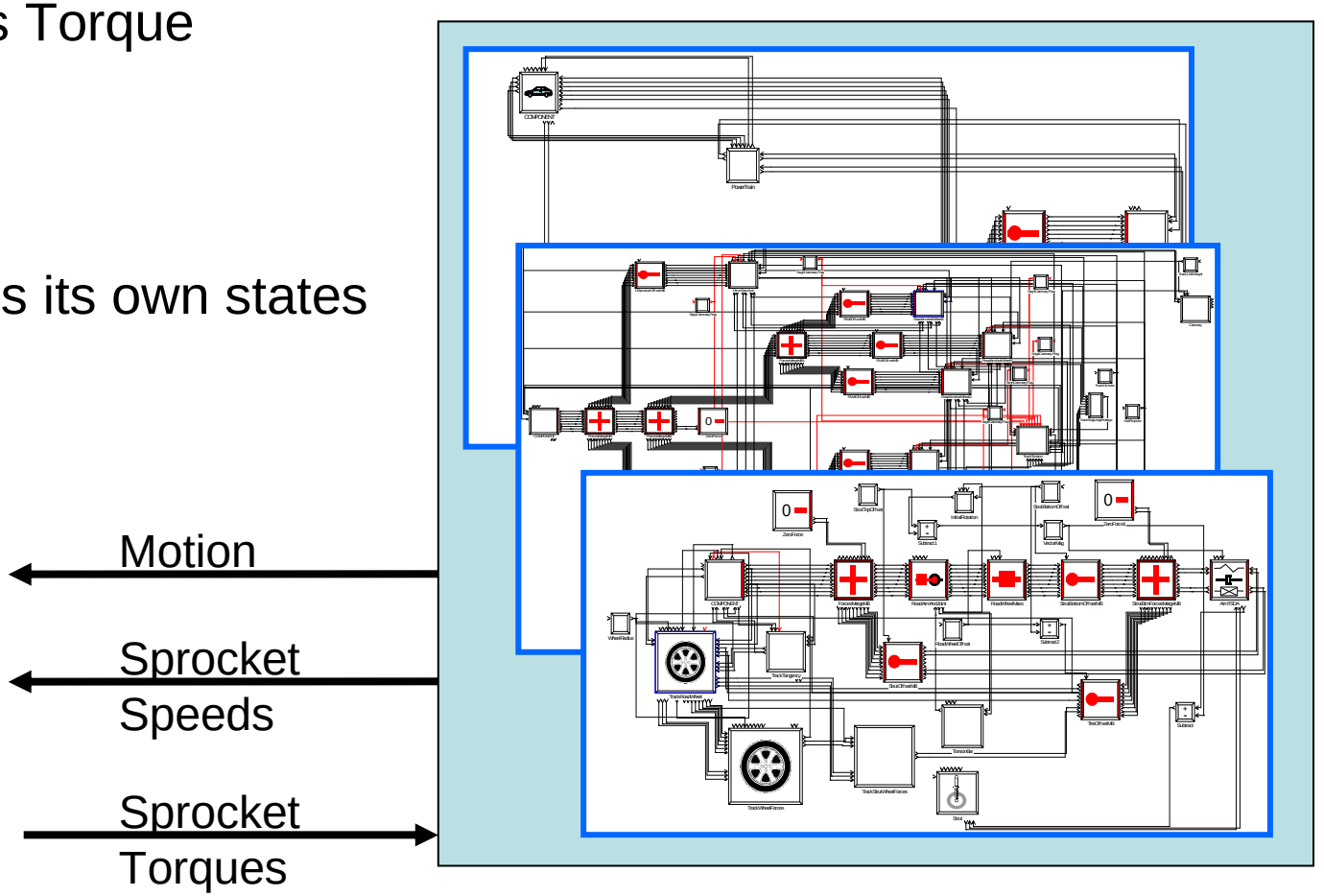




Vehicle Dynamics and Terrain

Vehicle Dynamics and Terrain

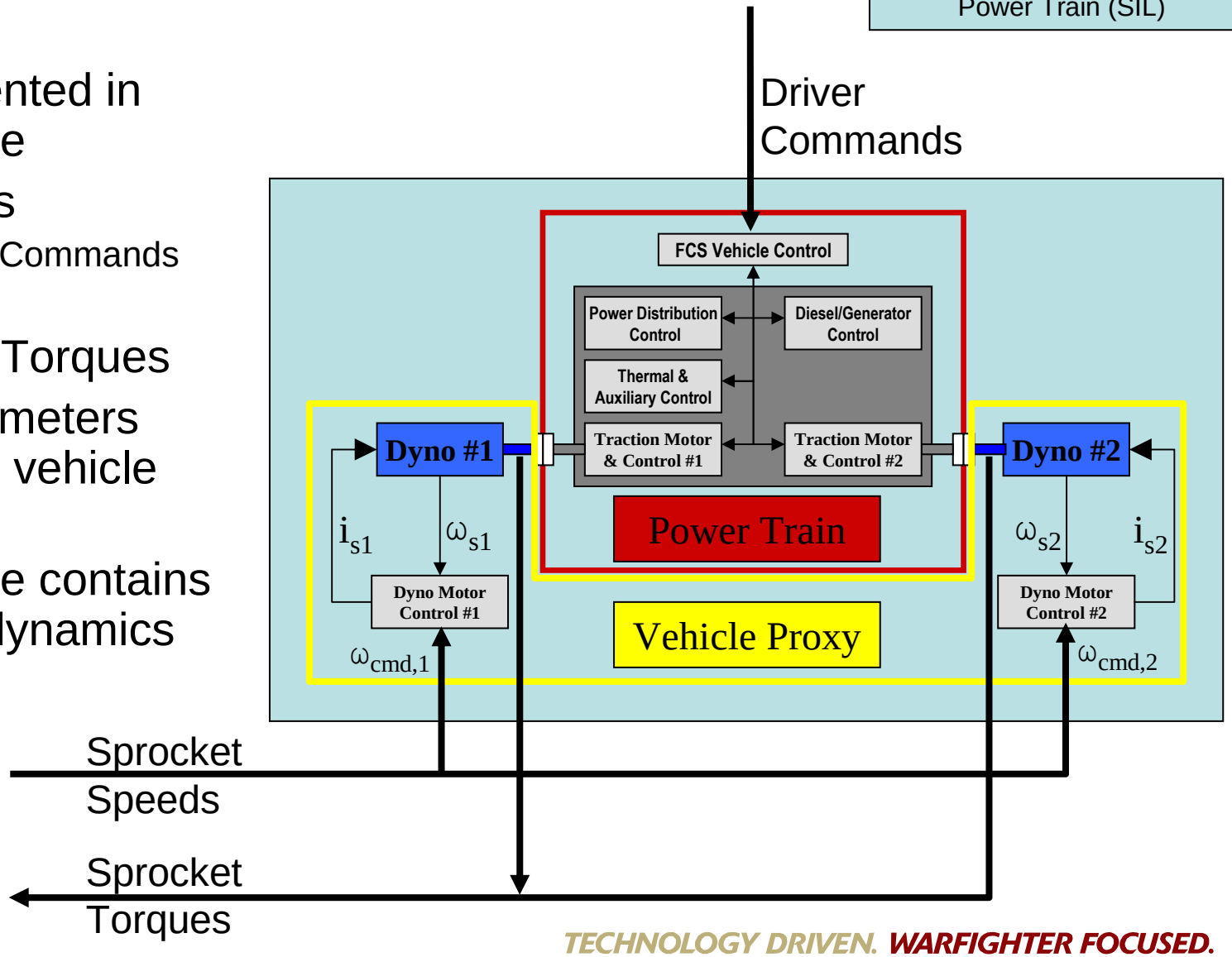
- Implemented in Dynamics Modeling Tool
- Receives Torque
- Outputs
  - Speed
  - Motion
- Integrates its own states



Power Train

Power Train (SIL)

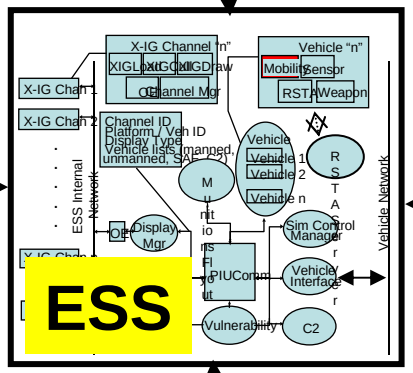
- Implemented in Hardware
- Receives
  - Driver Commands
  - Speed
- Outputs Torques
- Dynamometers serve as vehicle proxy
- Hardware contains implicit dynamics

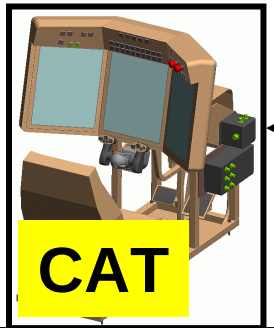


DCE Top Level Design

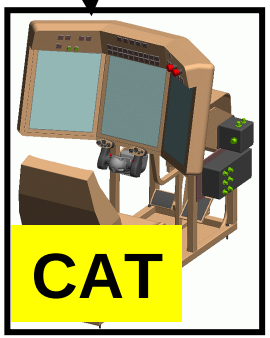
OTB

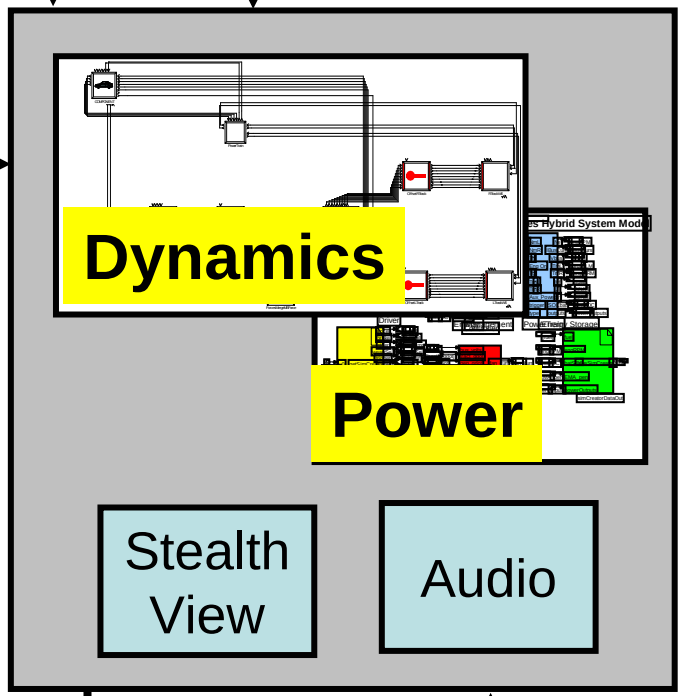
Long Haul





ESS





SimObserver

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Communication Channel Choice

Modem (56k bps)

- Analog/Digital
- Dedicated channel
- Connection-based
- Reliable
- No firewall
- Noise-based corruption
- ~350 ms round trip
- 1.4% loss rate

Internet

- Digital
- No dedicated channel
- Packet-based
- Moderately Reliable
- Firewall configuration required
- Dropped packets
- ~94 ms round trip
- 0.1% loss rate

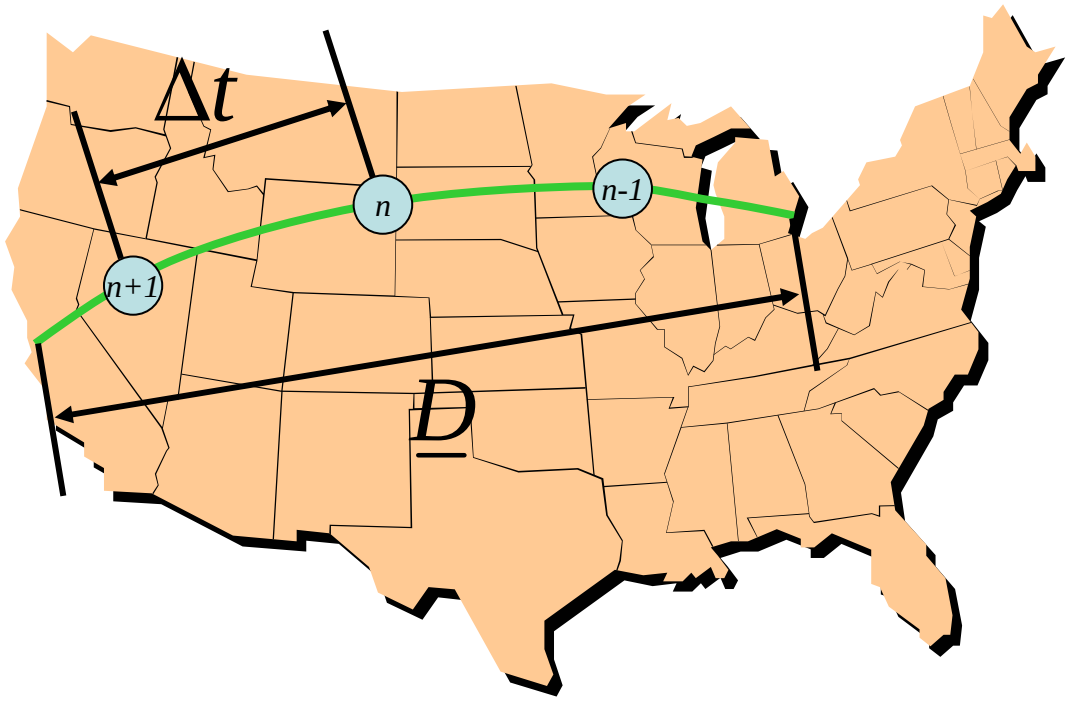
Protocol Choice

TCP $\Delta t \; ? \; \underline{D}$

- (Virtual) Connection
- Stream
- Reliable

UDP $\Delta t = \underline{D}$

- Connectionless
- Packet
- Unreliable



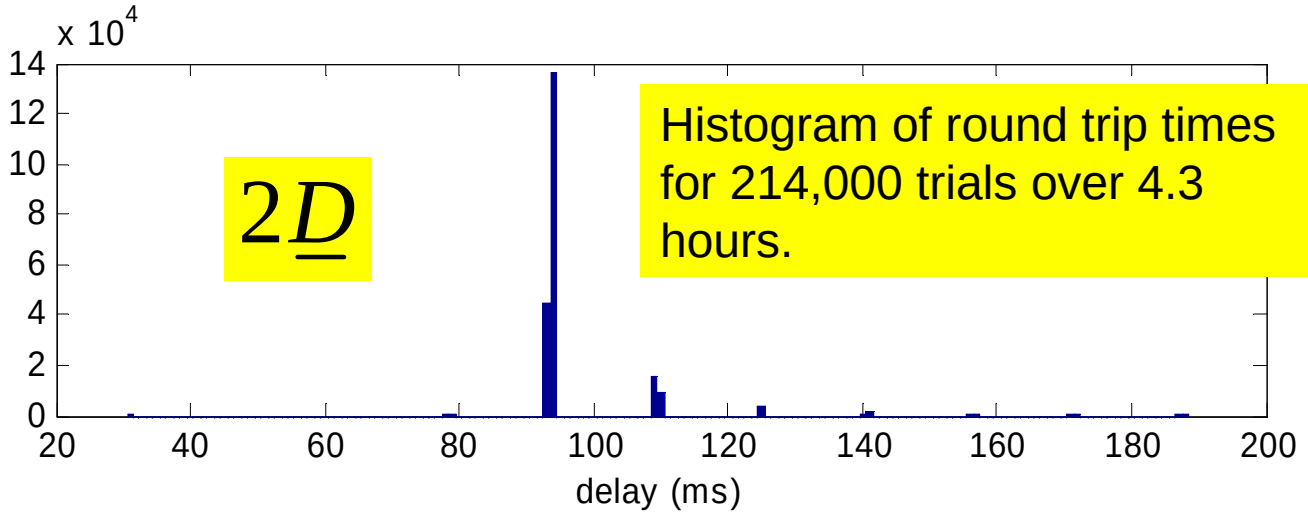
UDP Performance

- Round trip times
  - 78 ms to 188 ms
  - Most at 94 ms
  - Limit 26 ms
- 209 packets dropped
- Vehicle dynamics ~2 ms
- SIL ~10 ms

- Problems
  - Substantial delay
  - Delay jitter
  - Data loss

⇨ System Instability

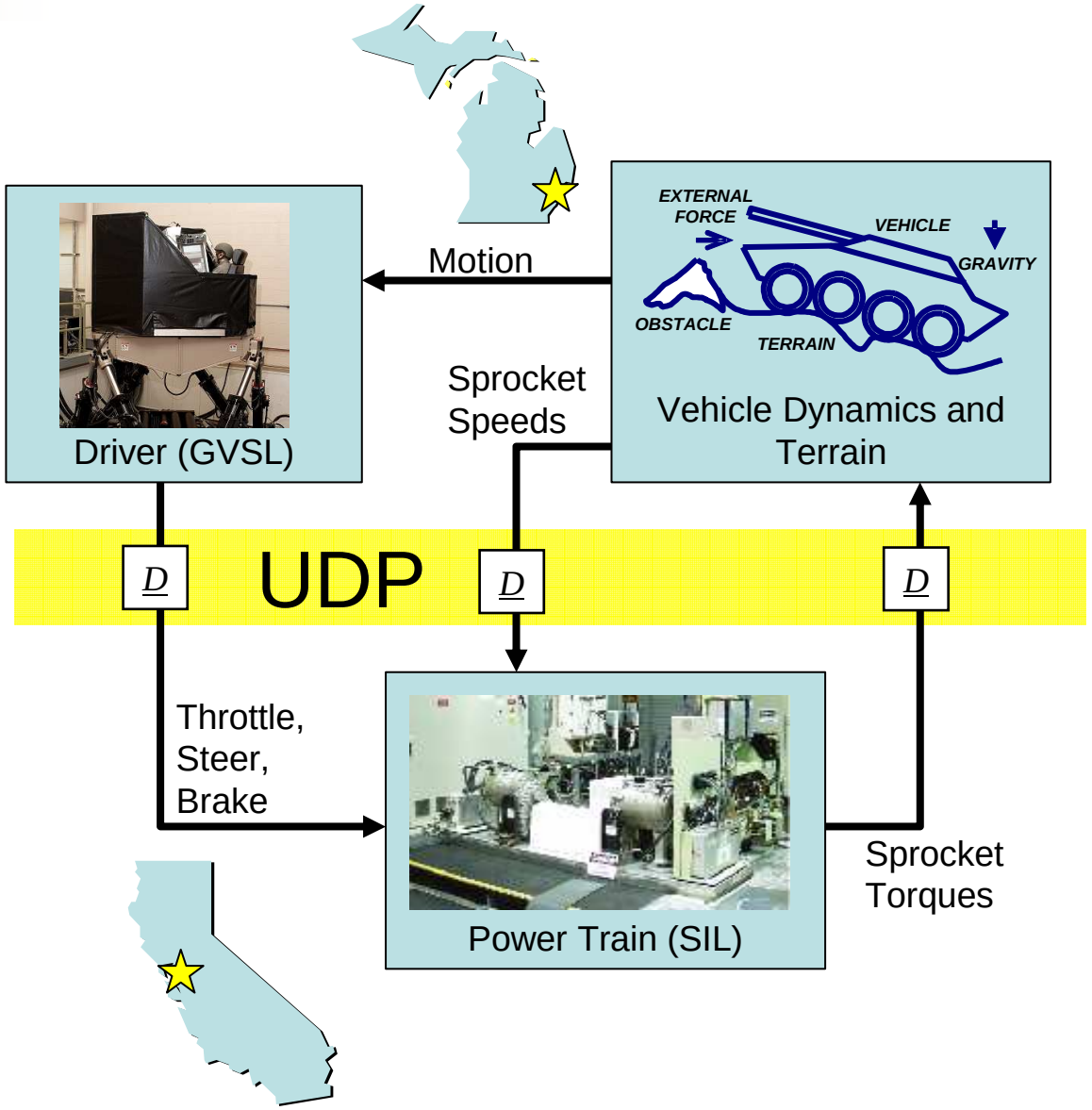
$\underline{D}$ is a random variable



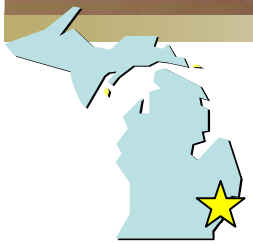
Histogram of round trip times for 214,000 trials over 4.3 hours.

Design A – Naïve Approach

- Delay > Dynamics
- Delay > SIL
- Simulator response
  - Driver → Motion
  - Increased by *2D*
- Safety risk to driver
- Damage risk to SIL
- Experimental quality degraded
- Potential instabilities



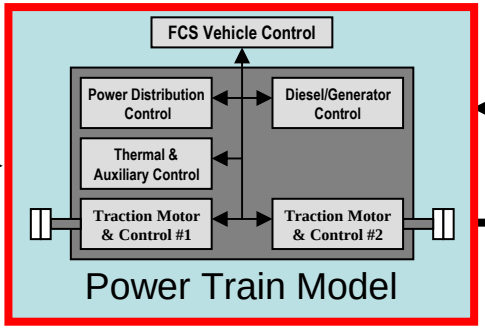
Design B – Parallel Simulations



Motion

Driver (GVSL)

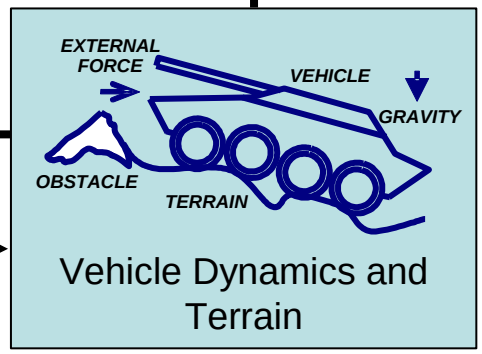
Throttle,
Steer,
Brake



Power Train Model

Sprocket
Speeds

Sprocket
Torques



Vehicle Dynamics and
Terrain

UDP

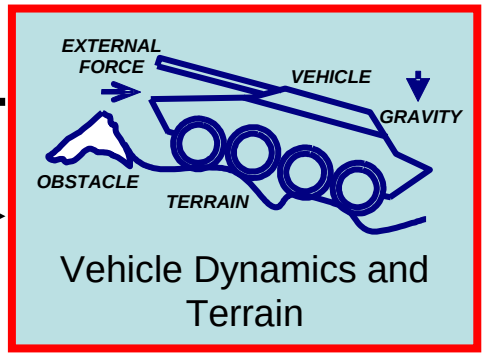
D

Throttle,
Steer,
Brake

Power Train (SIL)

Sprocket
Speeds

Sprocket
Torques



Vehicle Dynamics and
Terrain

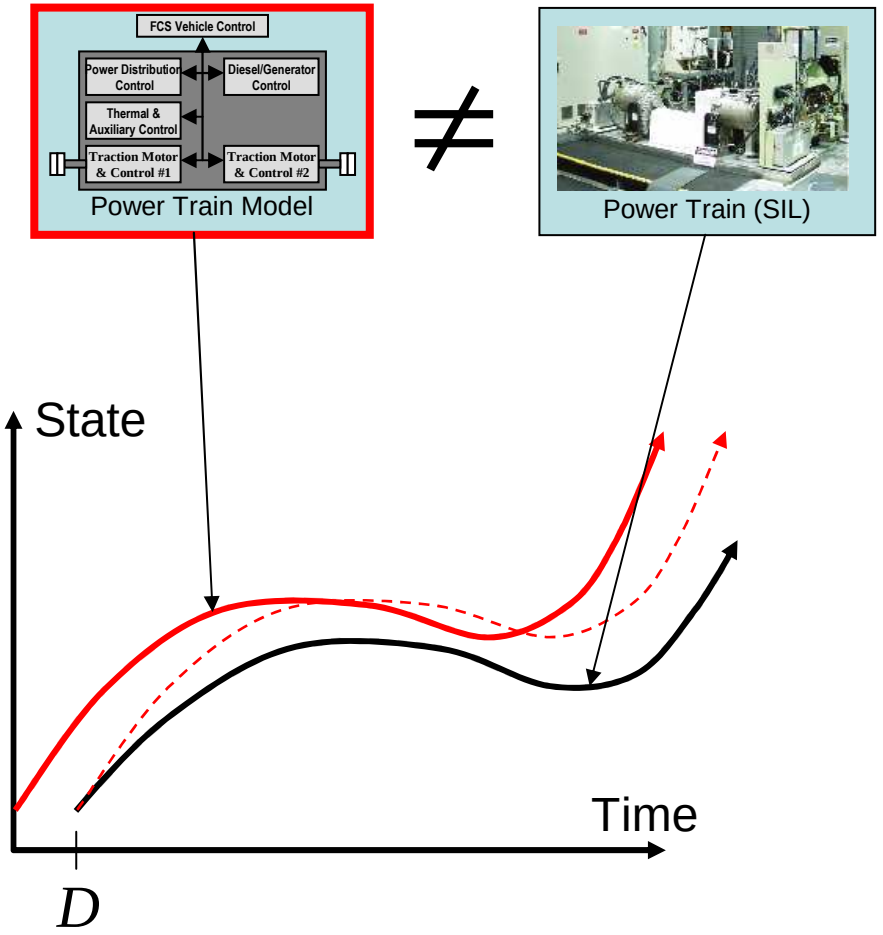
Design B – Evaluation

Pros

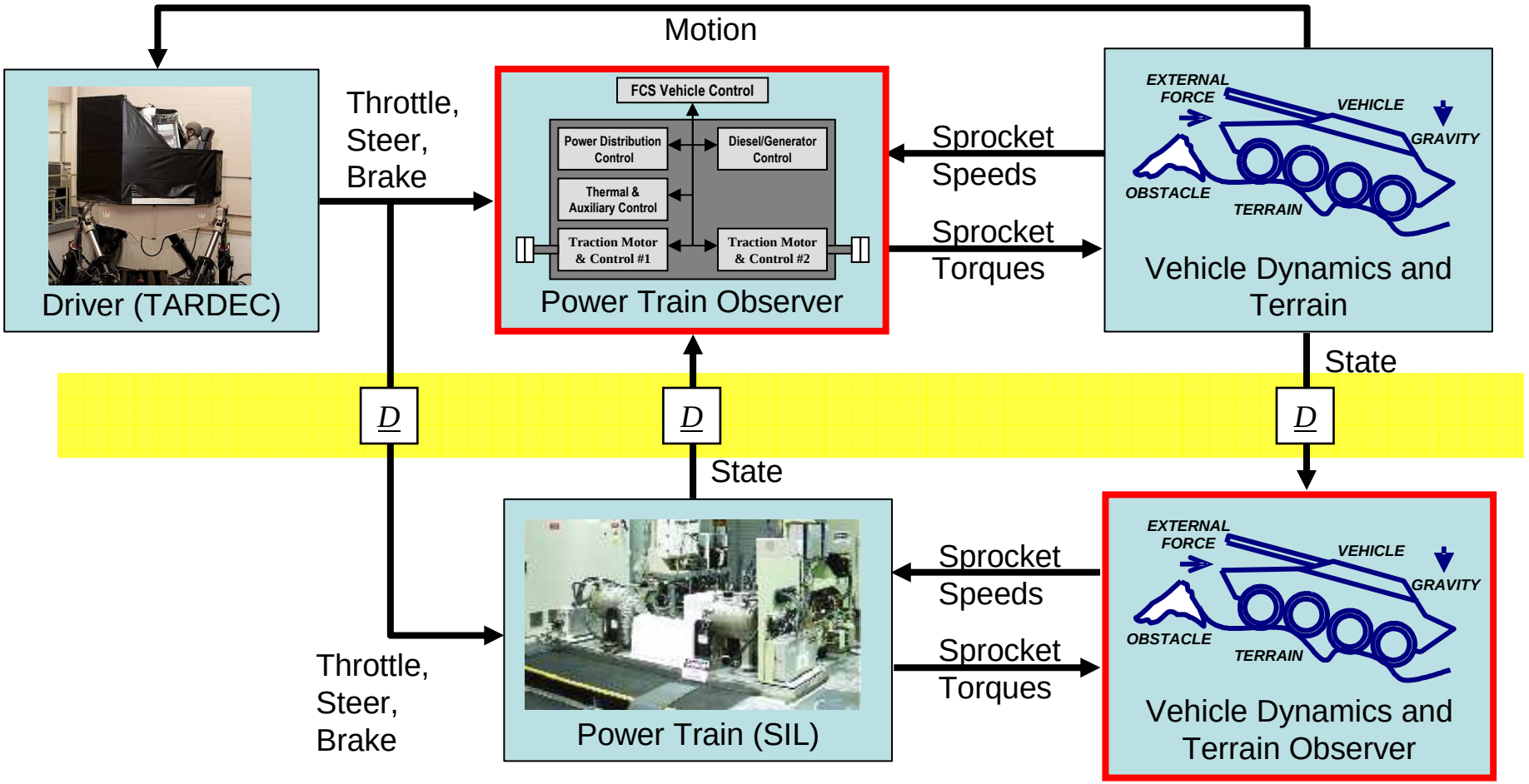
- SIL will receive proper commands delayed by D
- Immediate response
- The GVSL and SIL are not coupled

Cons

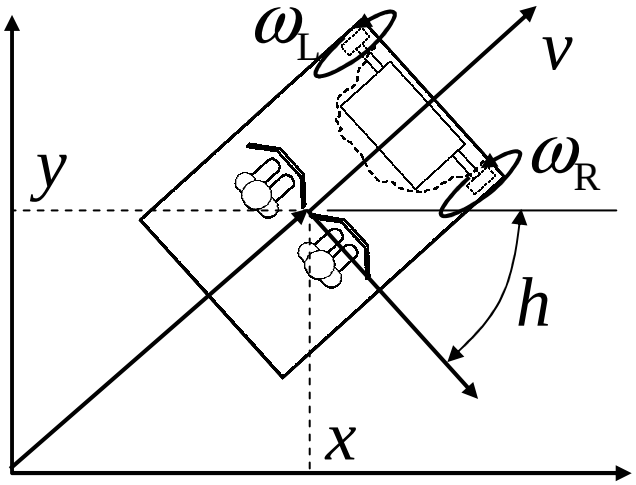
- The power train model does not exactly match the SIL
- The GVSL and the SIL will tend to drift apart over time.



Design C – Observers



Design C – Vehicle dynamics



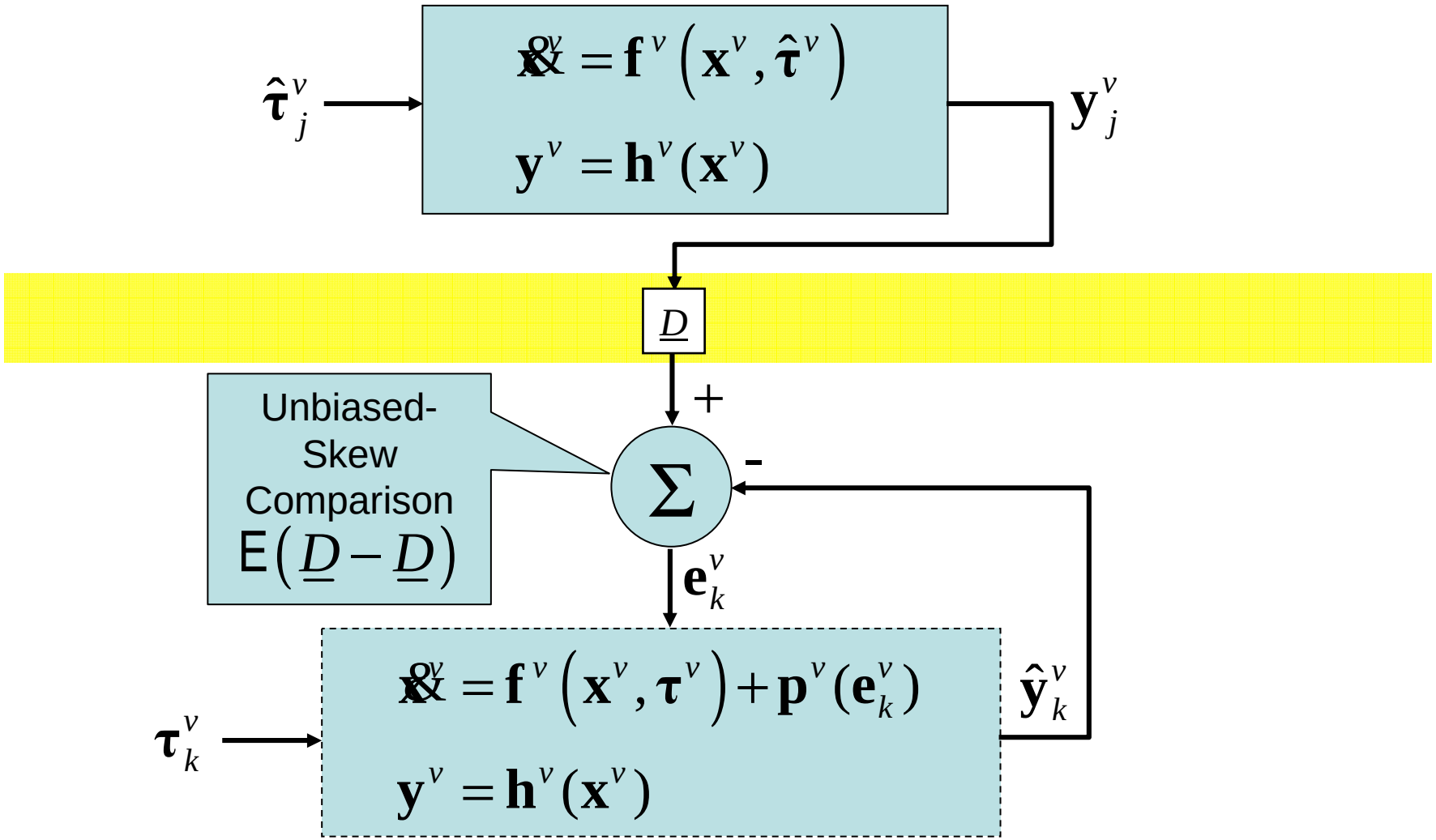
$$\boldsymbol{\tau}^v = \begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix}$$

$$\dot{\mathbf{x}}^v = \mathbf{f}^v\left(\mathbf{x}^v, \boldsymbol{\tau}^v\right)$$

$$\mathbf{y}^v = \mathbf{h}^v(\mathbf{x}^v)$$

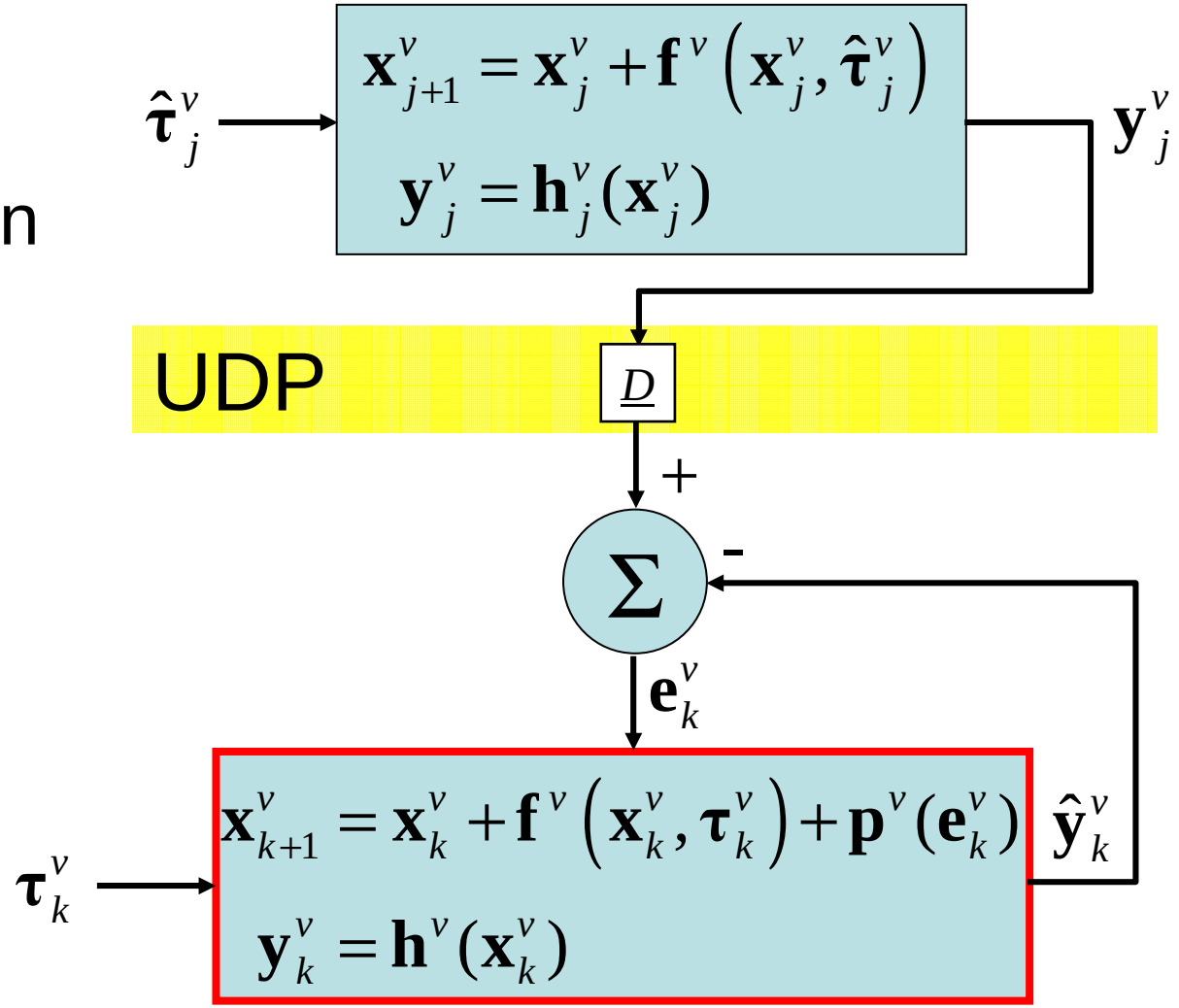
$$\mathbf{y}^v = \begin{bmatrix} x \\ y \\ h \\ v \\ \omega_L \\ \omega_R \end{bmatrix}$$

Design C – Vehicle Observer

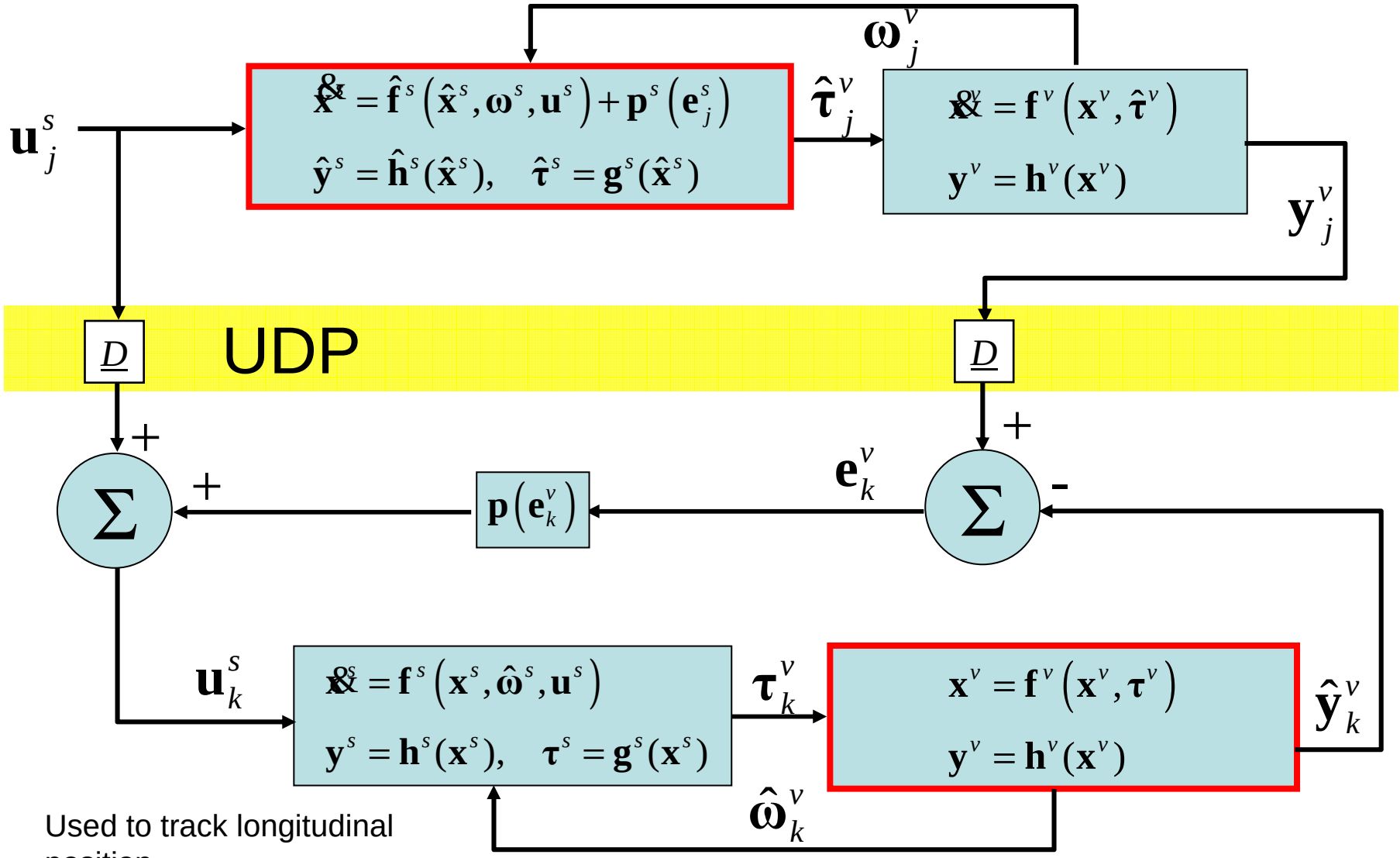


Vehicle Observer – Direct ("Skyhook")

- Imposes an artificial force on the vehicle
- Used to track
  - Lateral position
  - Heading
  - Sprocket speed

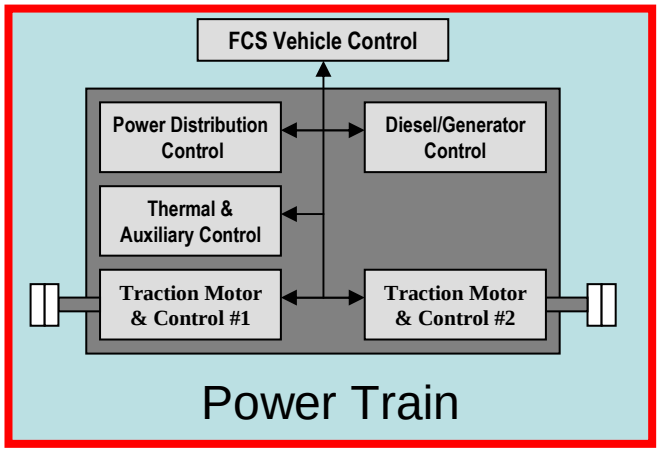


Vehicle Observer – Indirect ("Augmented Input")



- Used to track longitudinal position

Design C – Power train dynamics



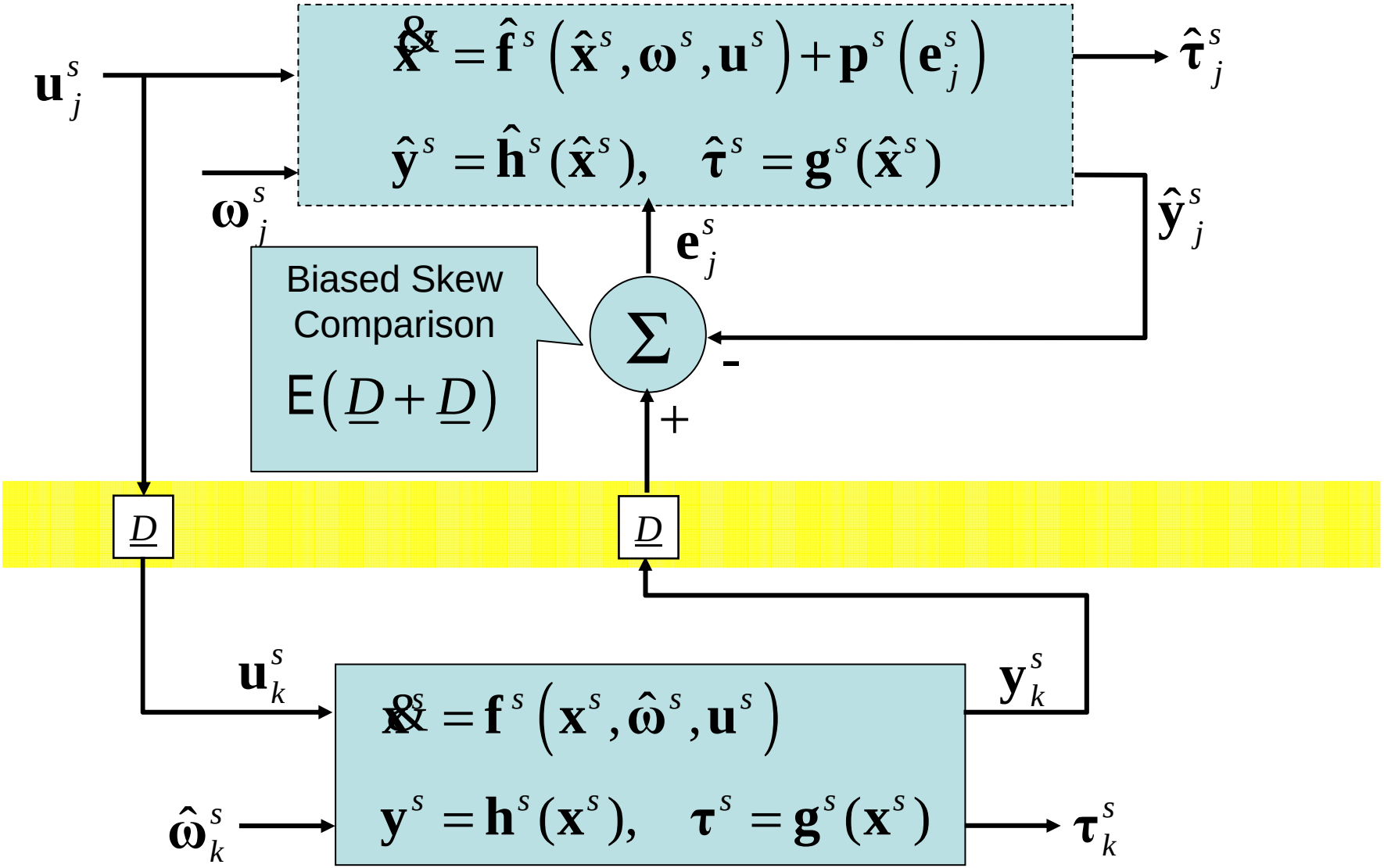
$$\mathbf{u}_k^s = \begin{bmatrix} t \\ s \\ b \end{bmatrix} \qquad \boldsymbol{\omega}_k^s = \begin{bmatrix} \omega_{\mathrm{L}} \\ \omega_{\mathrm{R}} \end{bmatrix}$$

$$\dot{\mathbf{x}}^s = \mathbf{f}^s\left(\mathbf{x}^s, \boldsymbol{\omega}^s, \mathbf{u}^s\right)$$

$$\mathbf{y}^s = \mathbf{h}^s(\mathbf{x}^s), \quad \boldsymbol{\tau}^s = \mathbf{g}^s(\mathbf{x}^s)$$

$$\mathbf{y}_k^s = \begin{bmatrix} SOC_{\mathrm{b}} \\ V_{\mathrm{bus}} \\ \omega_{\mathrm{e}} \\ \mathrm{l}_{\mathrm{f}} \\ T_{\mathrm{b}} \\ \mathrm{M} \end{bmatrix} \qquad \boldsymbol{\tau}_k^s = \begin{bmatrix} \tau_{\mathrm{L}} \\ \tau_{\mathrm{R}} \end{bmatrix}$$

Design C – Power Train Observer



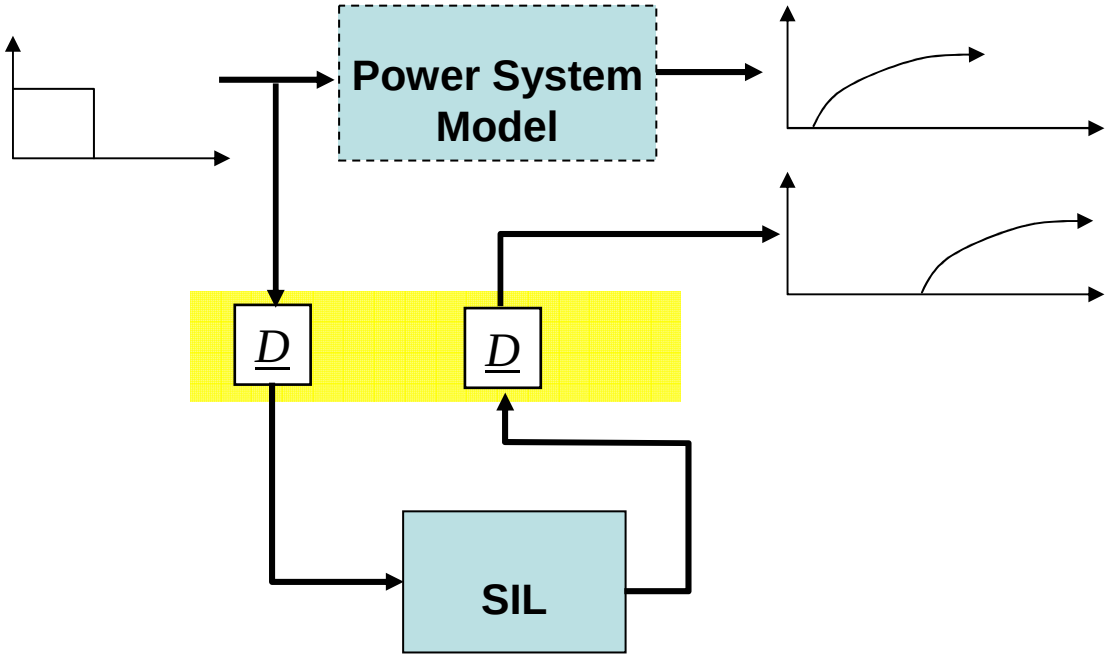
Design C – Evaluation

Pros

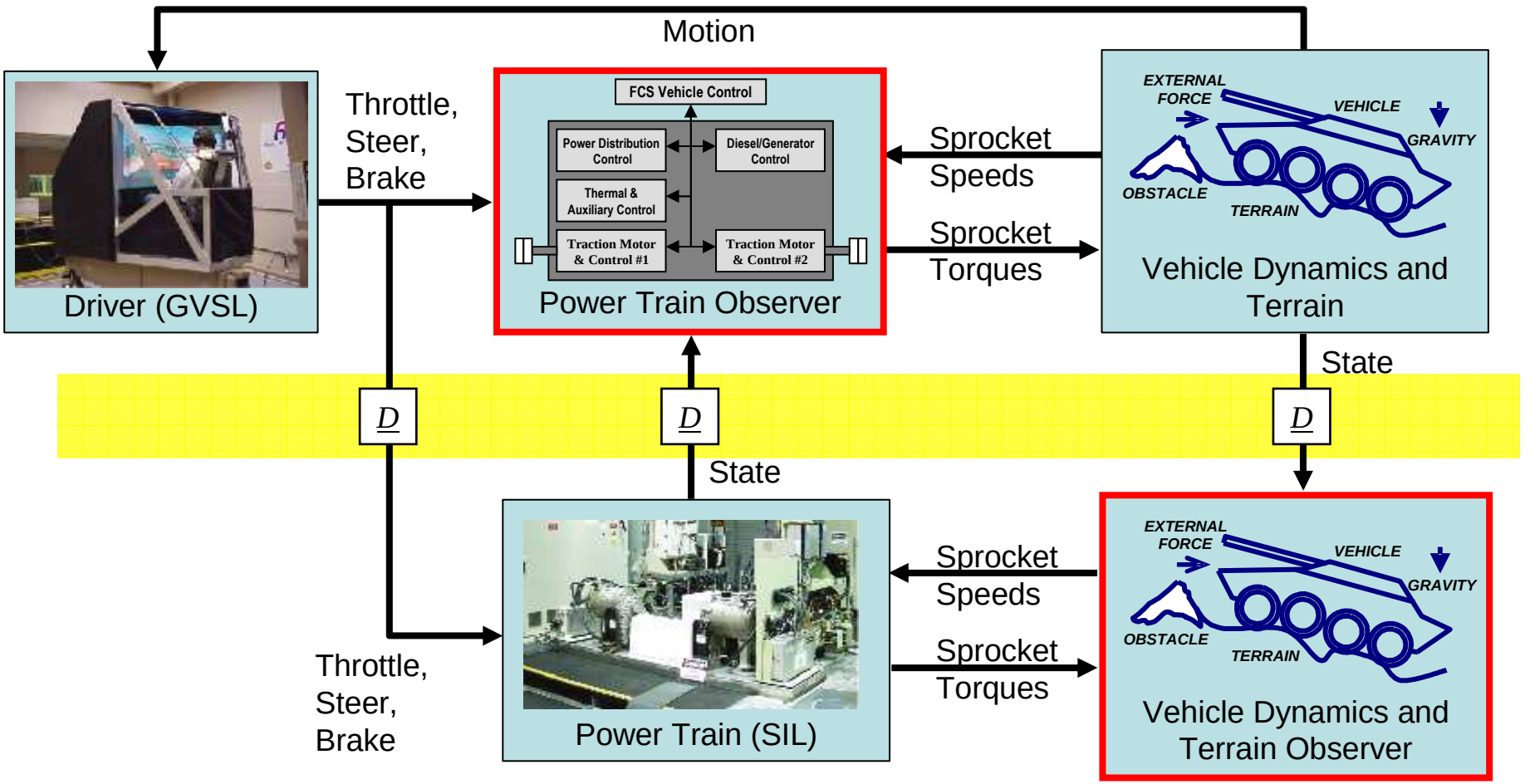
- States should track
- Delay is approximately negated in vehicle error

Cons

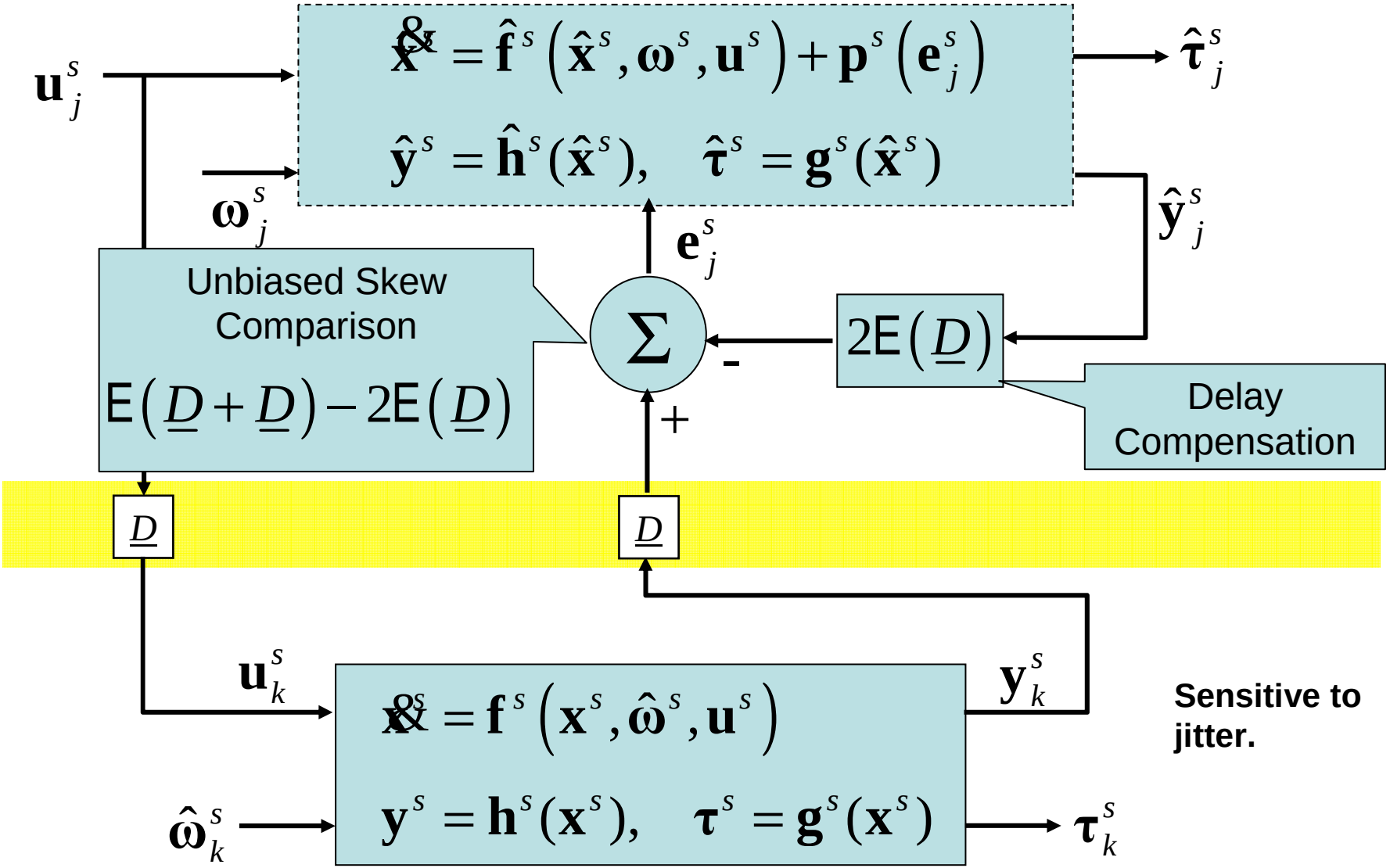
- Delay is approximately doubled in power train error
- Error contains time skew



Design D – Delay Compensation



Design D – Power Train Observer Delay Compensation



Sensitive to jitter.

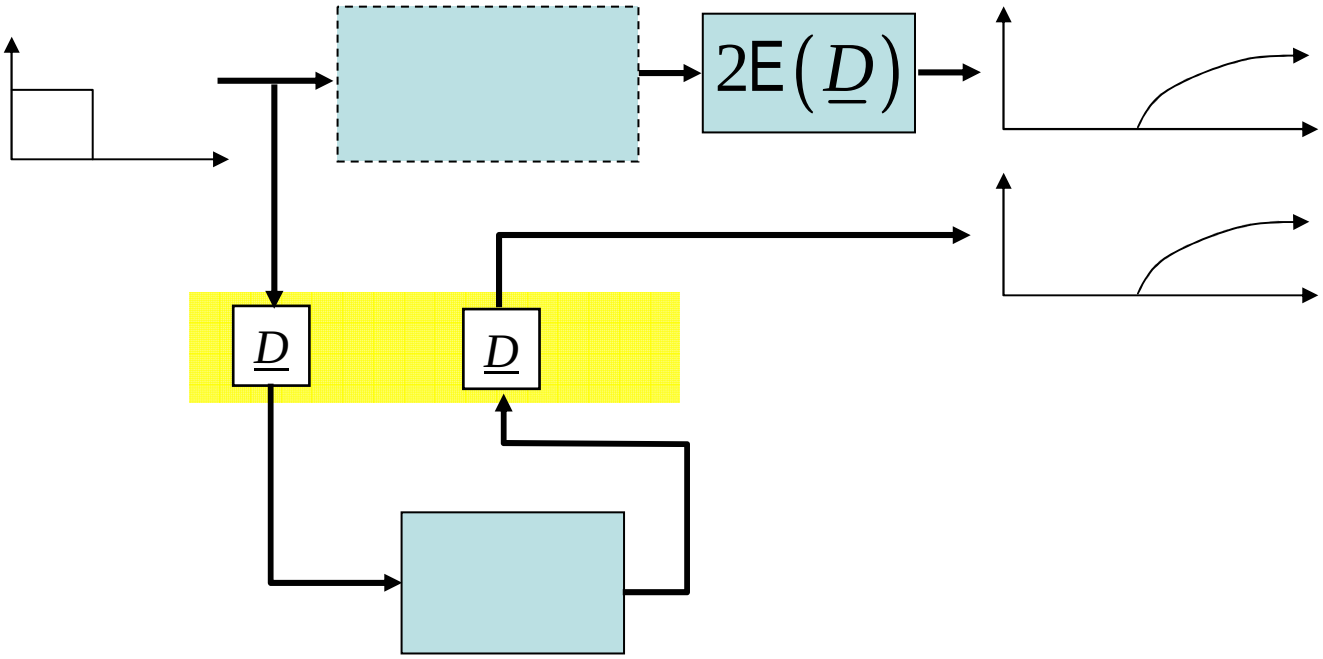
Design D – Evaluation

Pros

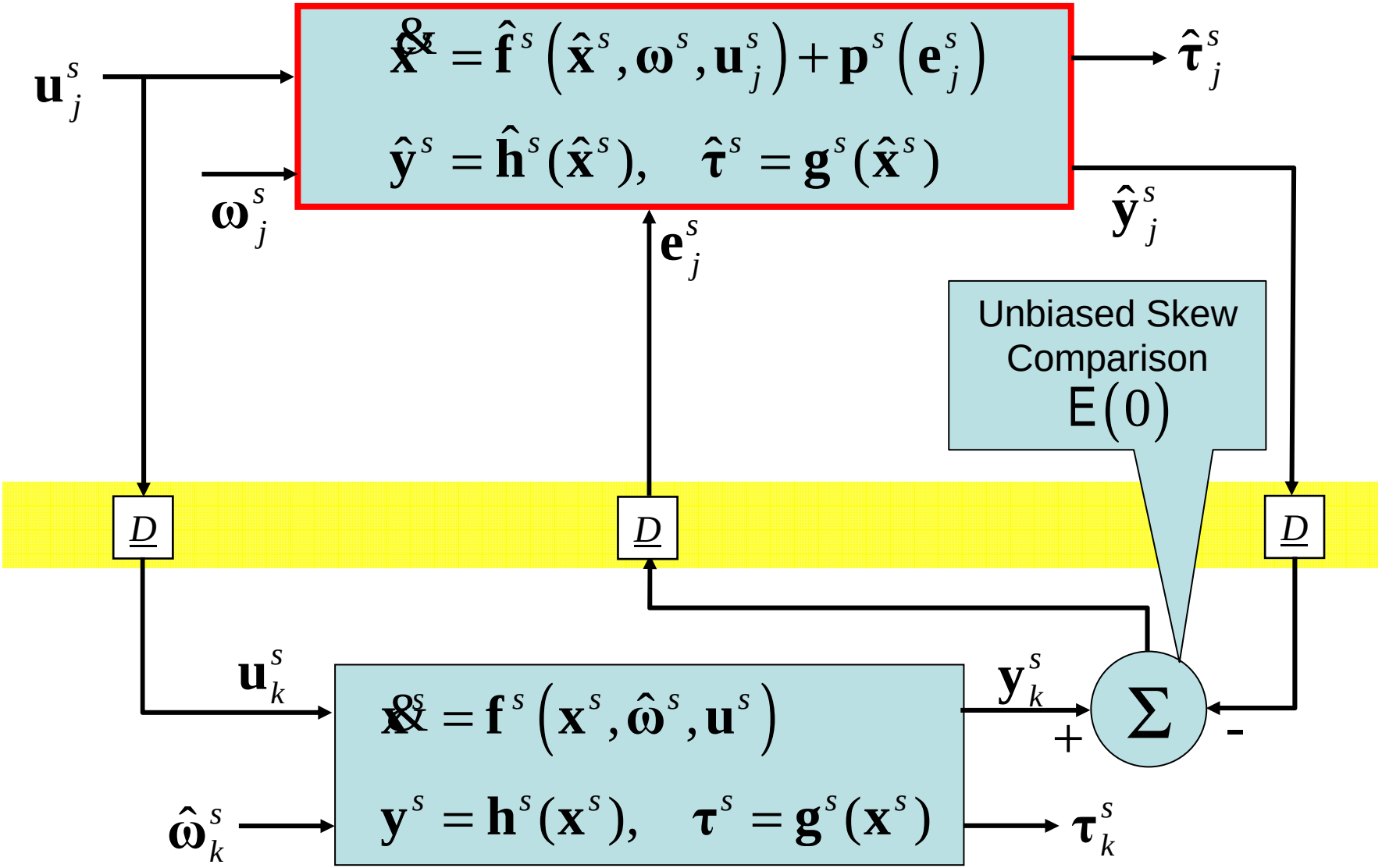
- Unbiased estimate of the error

Cons

- Does not account for variance in delay (jitter).
- Does not account for data loss.



Power Train Observer (un-skewed, robust)



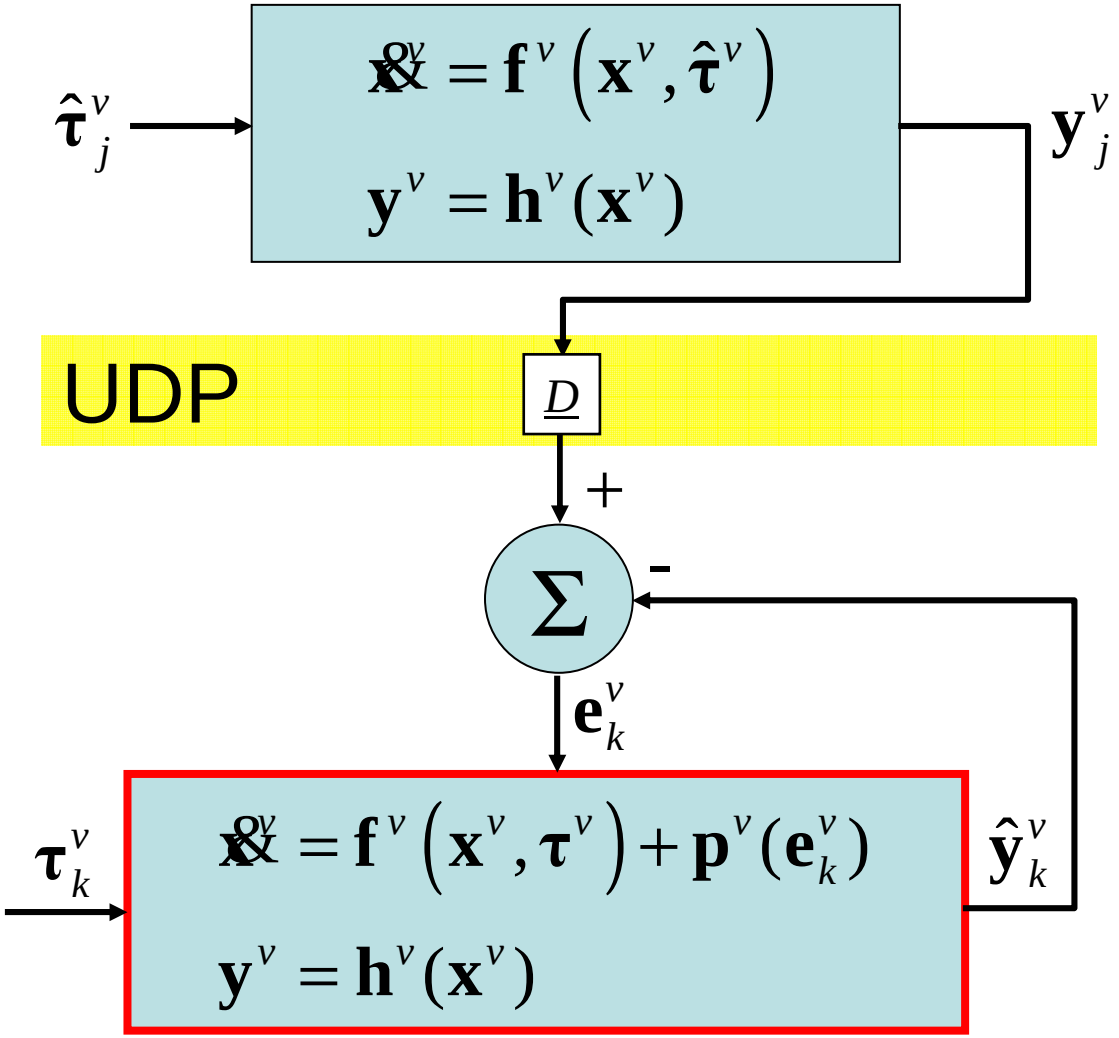
The Correction Term

- Ideas from sliding mode control were used to define the correction term.
- We used the sliding surface

$$s = \left(\frac{d}{dt} + \lambda \right) e$$

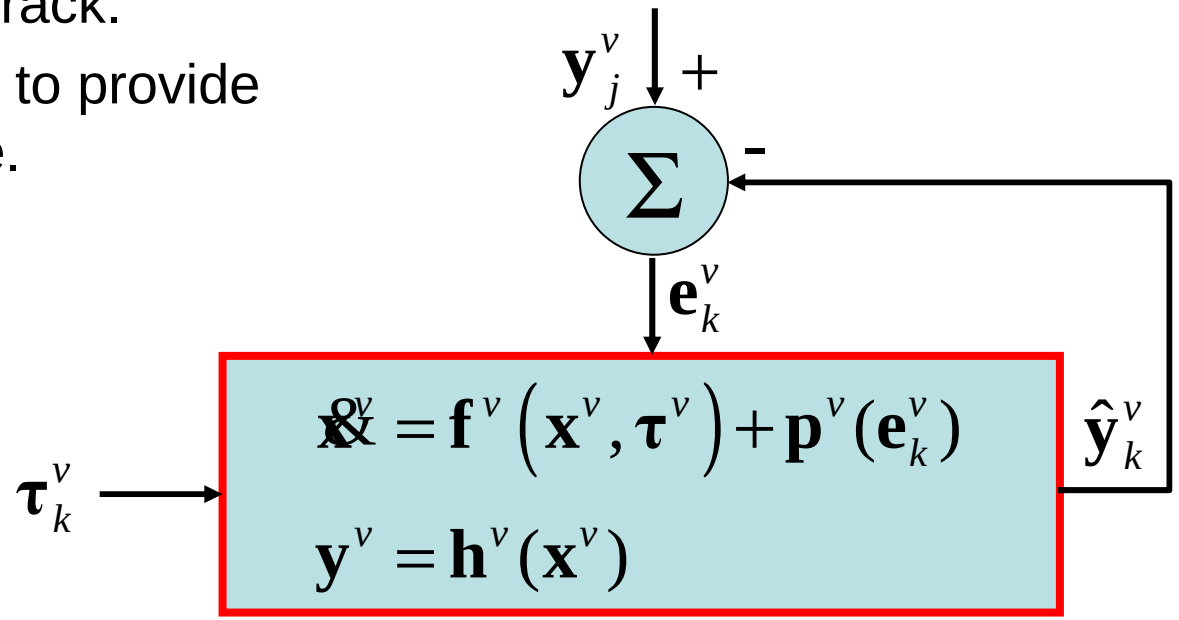
for some degree of freedom .

- We then devise a controller to drive s to 0.
- Our control action targets the acceleration terms of $\ddot{\mathbf{x}}$
- We use the “robust” term of the SMC with a transition region to avoid chattering.



Aggressiveness of Control

- $\mathbf{p}^{v}(\mathbf{e}_k^{v})$ directly affects state rates.
- States are fully accessible (via rates).
- If allowed, may directly manipulate states.
- It is best to manipulate states in a rational way (i.e., IAW non-holonomic constraints)
- It is best to allow the correction term to gently keep system on track.
- Allow forward dynamics to provide instantaneous response.

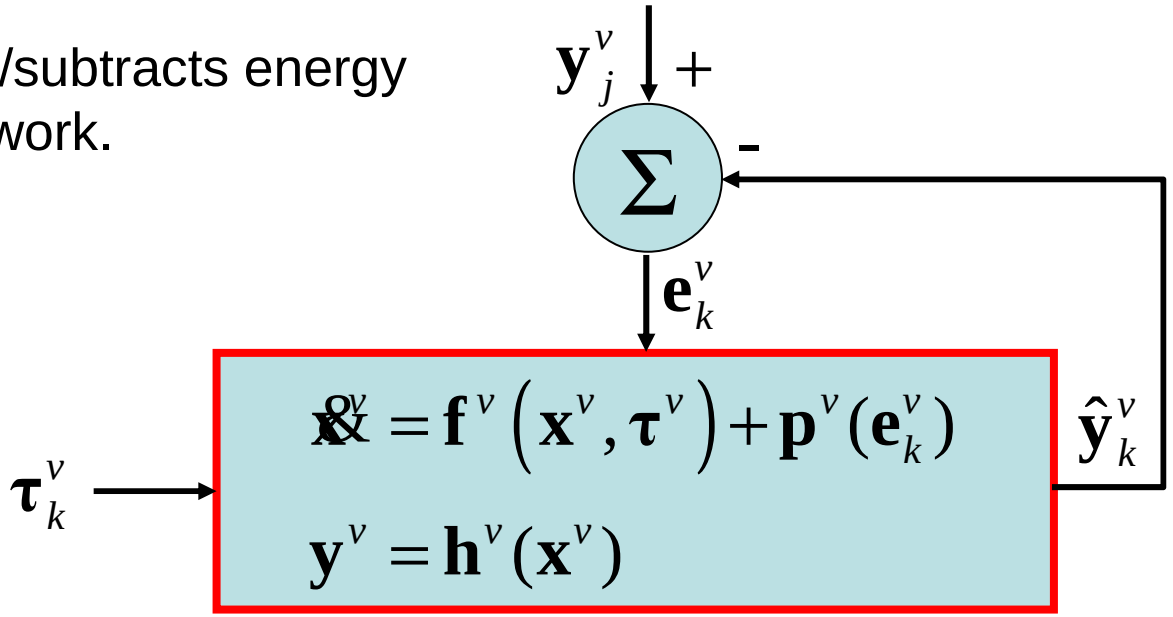


Leaked Energy

- $\mathbf{p}^v(\mathbf{e}_k^v)$ imposes an artificial "force" on the vehicle
- It affects the location and velocity.
- Ideally $\mathbf{f}^v\left(\mathbf{x}^v, \boldsymbol{\tau}^v\right) = \mathbf{p}^v(\mathbf{e}_k^v)$
- If $\mathbf{p}^v$ affects only acceleration terms then $\mathbf{v}^T\mathbf{p}^v$ is an energy like term (normalized to unit mass).
- The correction term adds/subtracts energy from the system; it does work.
- We use

$$\int_0^t \mathbf{v}^T\mathbf{p}^v d\tau$$

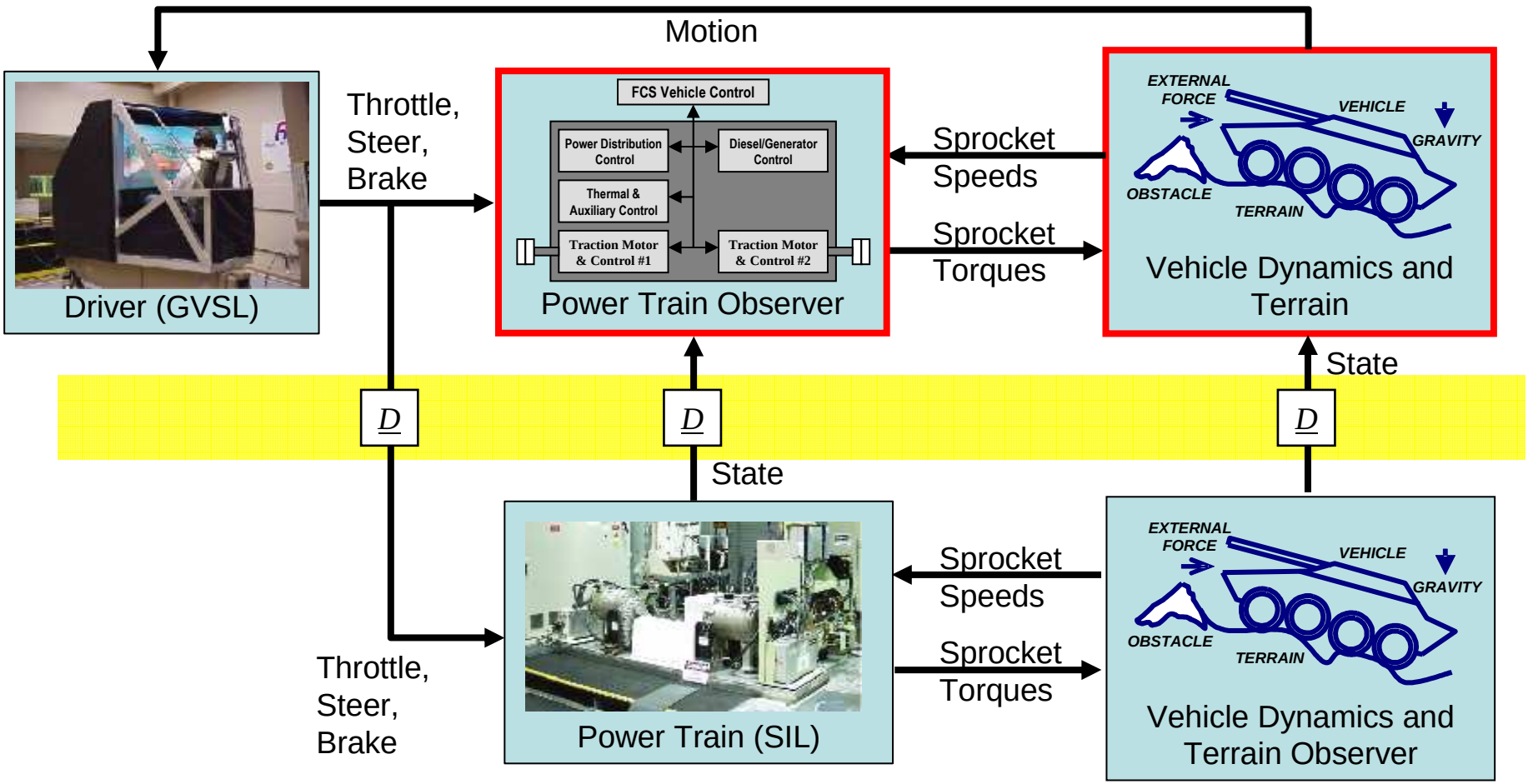
to measure the accuracy of the observer.



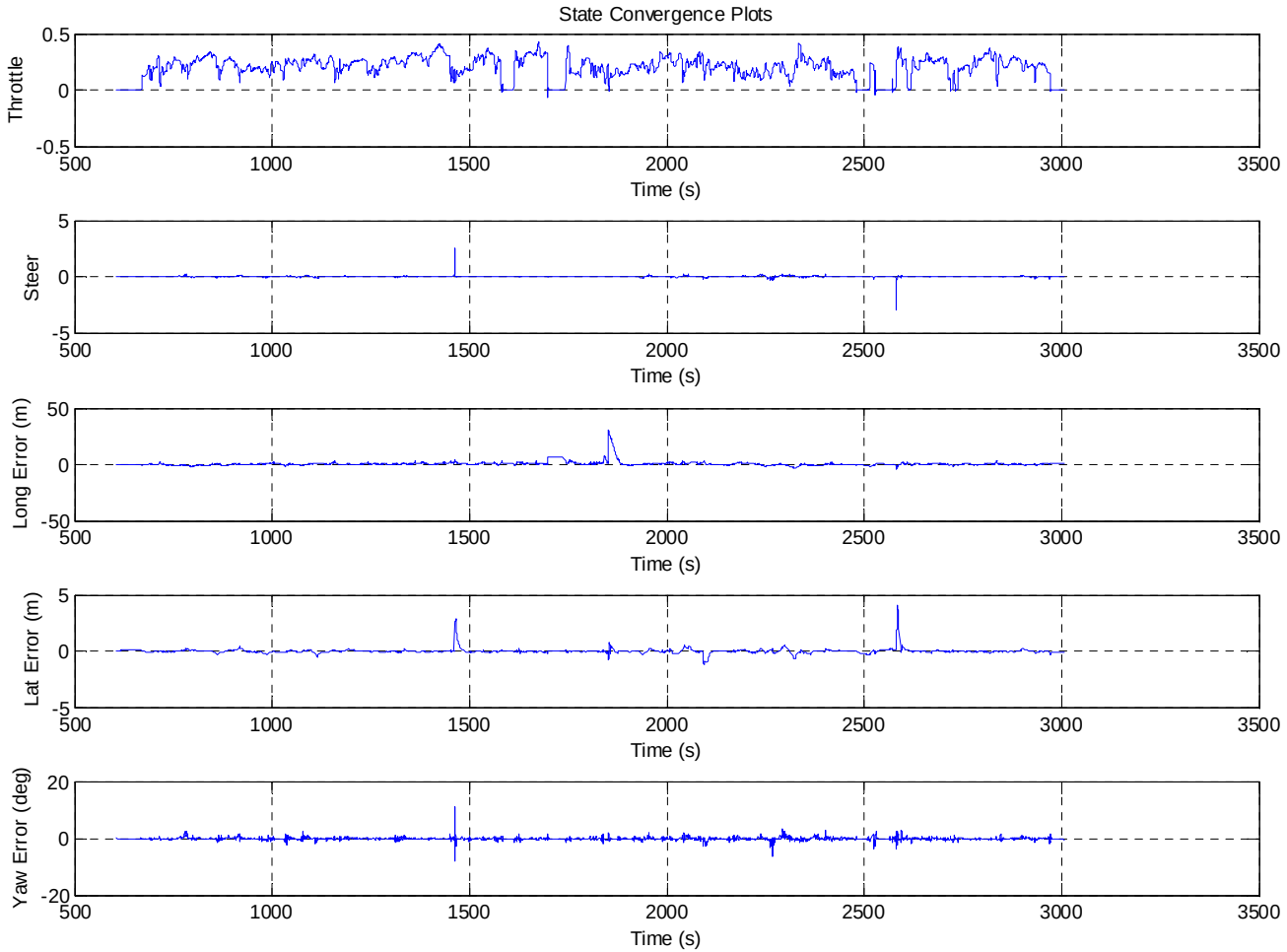
Safety Robustness

- Both TARDEC and SIL have parallel simulations running.
- Only TARDEC has human operator.
- Both sides set thresholds on state convergence error.
- If threshold is exceeded, the SIL is dropped off line and TARDEC continues.
- Additionally, health flags are sent back and forth regarding major system readiness.

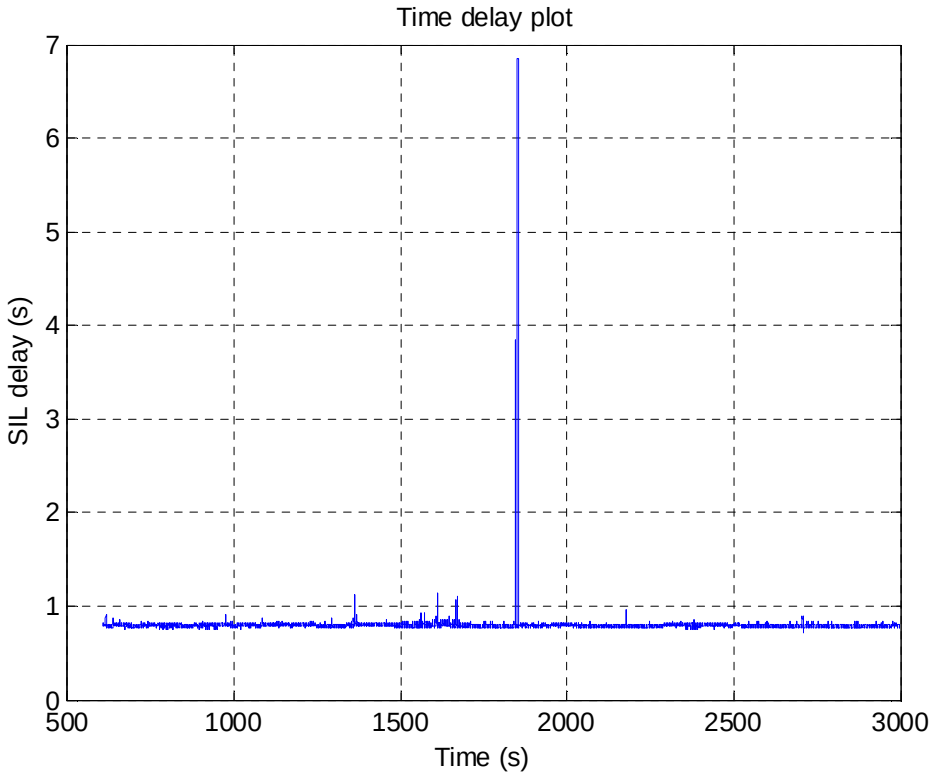
Design
E – Local Observers



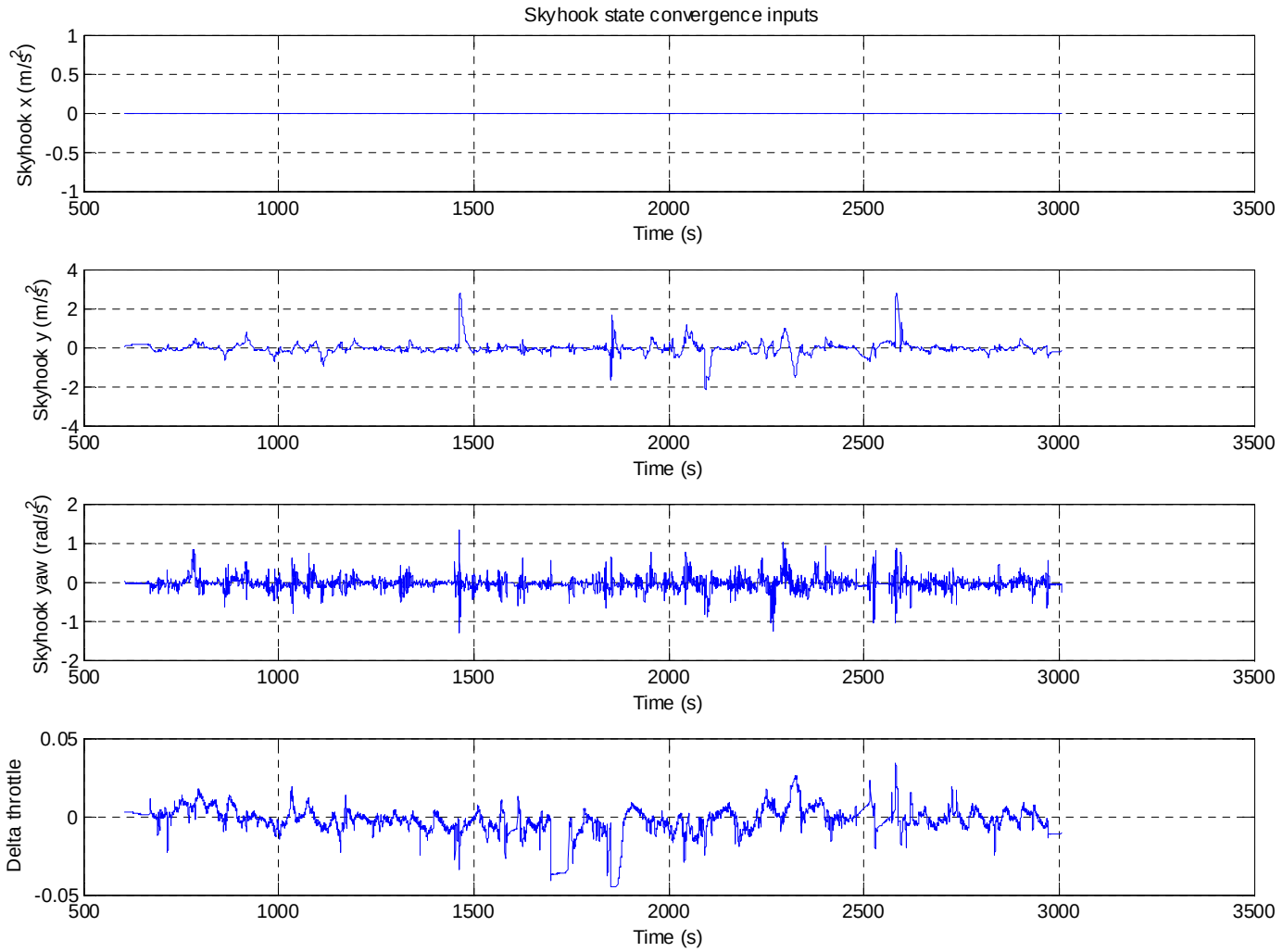
Driver commands and SC errors



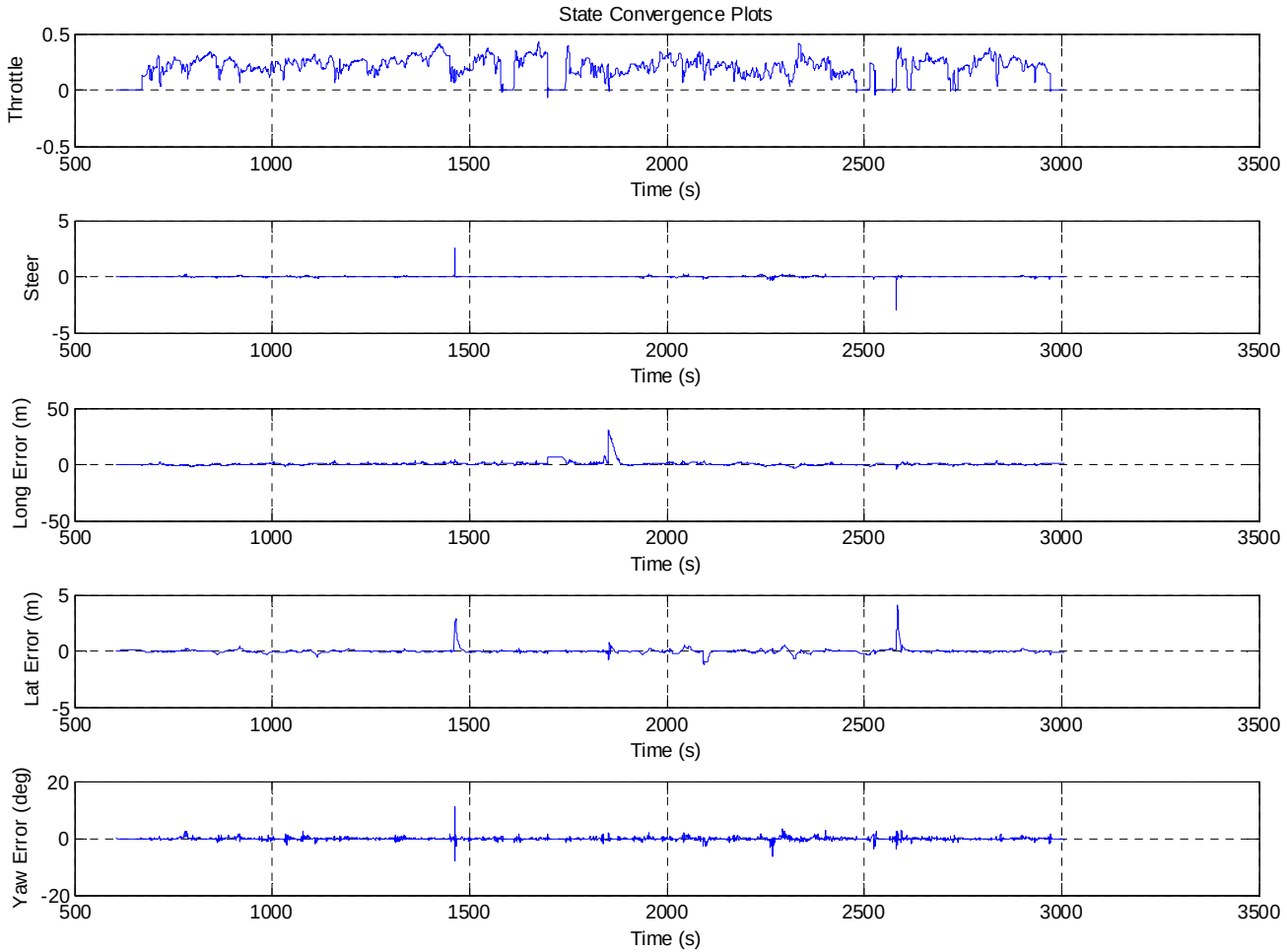
Time Delay


Time delay plot
SIL delay (s)
Time (s)
0
1
2
3
4
5
6
7
500
1000
1500
2000
2500
3000

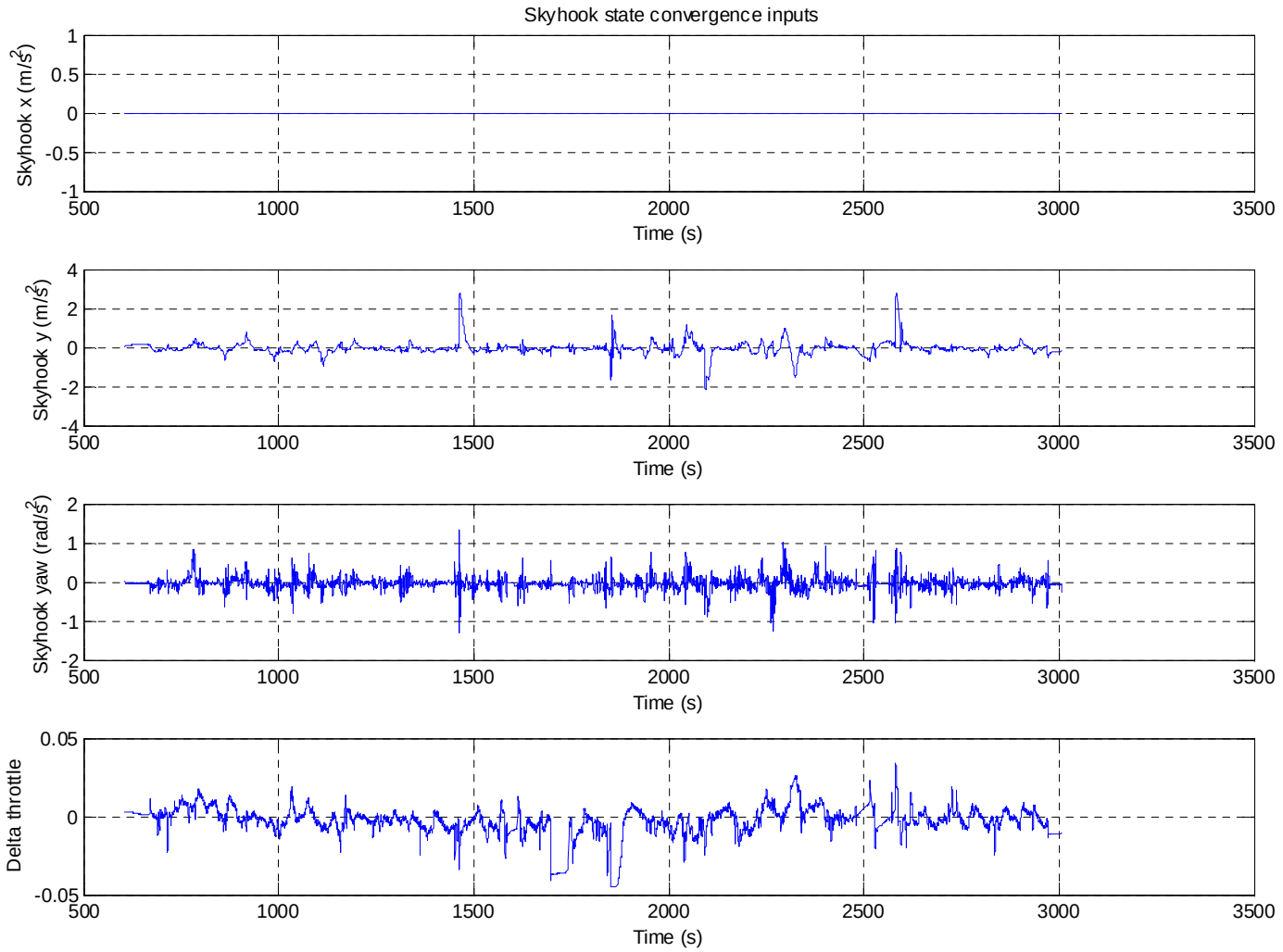
Artificial inputs



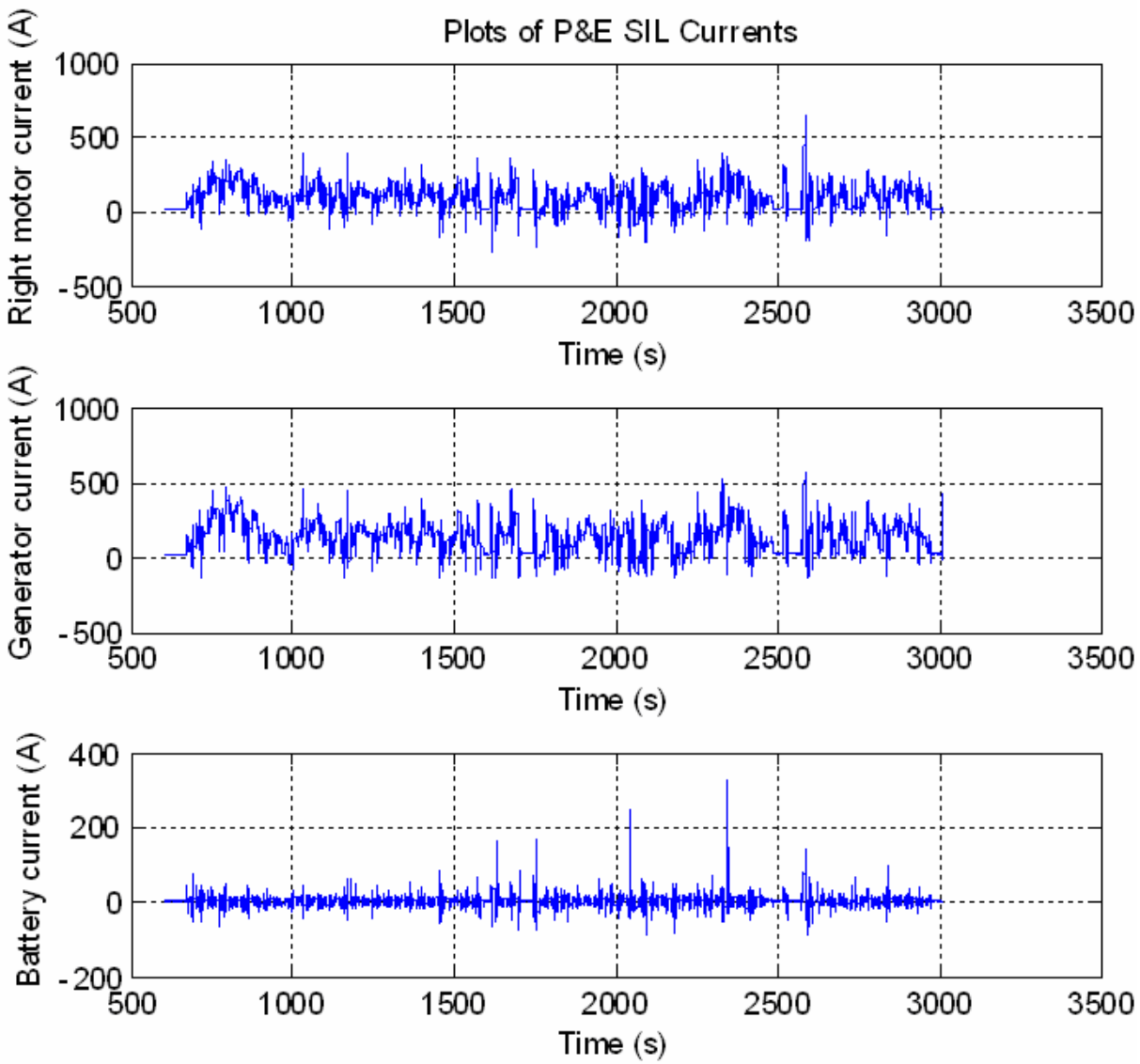
Driver commands and SC errors



Artificial inputs



SIL Performance



Main Results

The only large state convergence errors occurred during either a significant time delay or an extreme driving event.

Leaked mobility energy: Less than 3% of total input energy

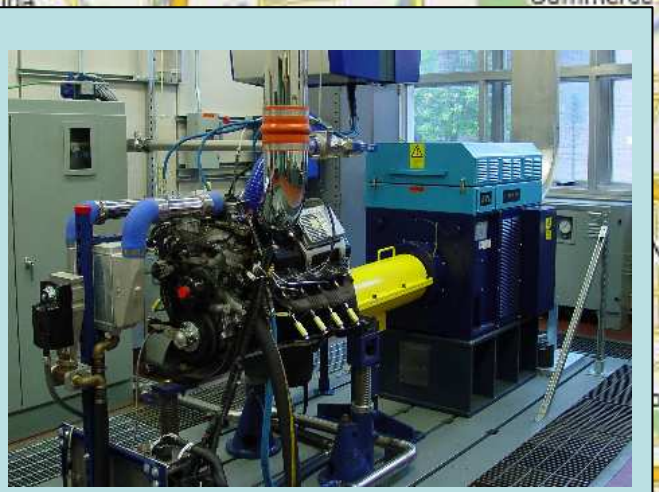
Leaked powertrain energy: Less than 2% of total input energy

Turret/Gun errors: Less than 10 degrees

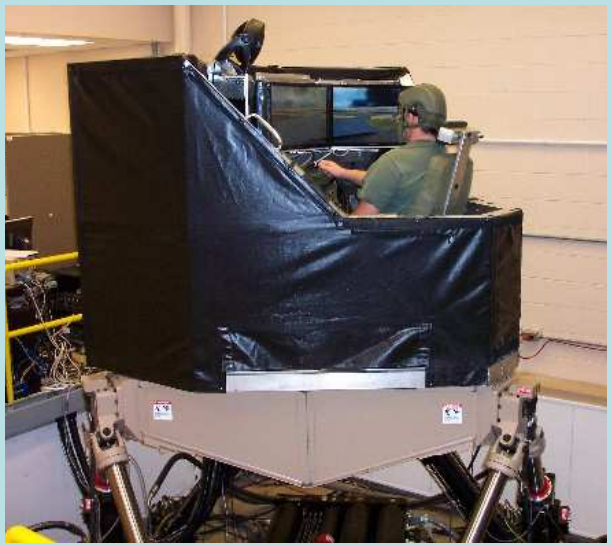
Bus voltage errors: Less than 80 volts

Driver didn’t notice any SC-induced oscillations

Continuing Work



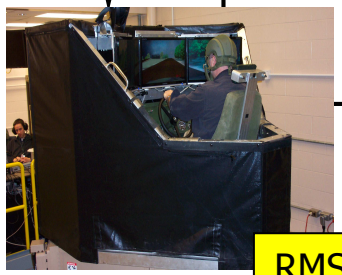
Engine/Dynamometer



RMS/Dynamics

Map Courtesy of Google™ Maps

Observer Free Approach



RMS

$[b, s, g]$

t

Long-haul Comp.

τ

ω

Vehicle Model

$[p, \dot{p}, \ddot{p}]$

Net QOS

Internet

D

D

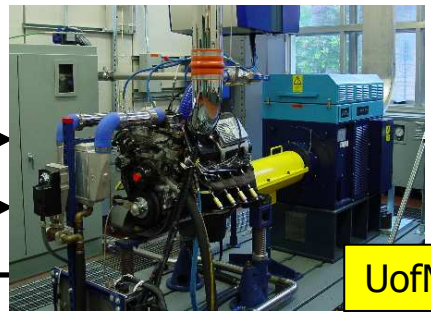
Net QOS

Long-haul Comp.

t

ω

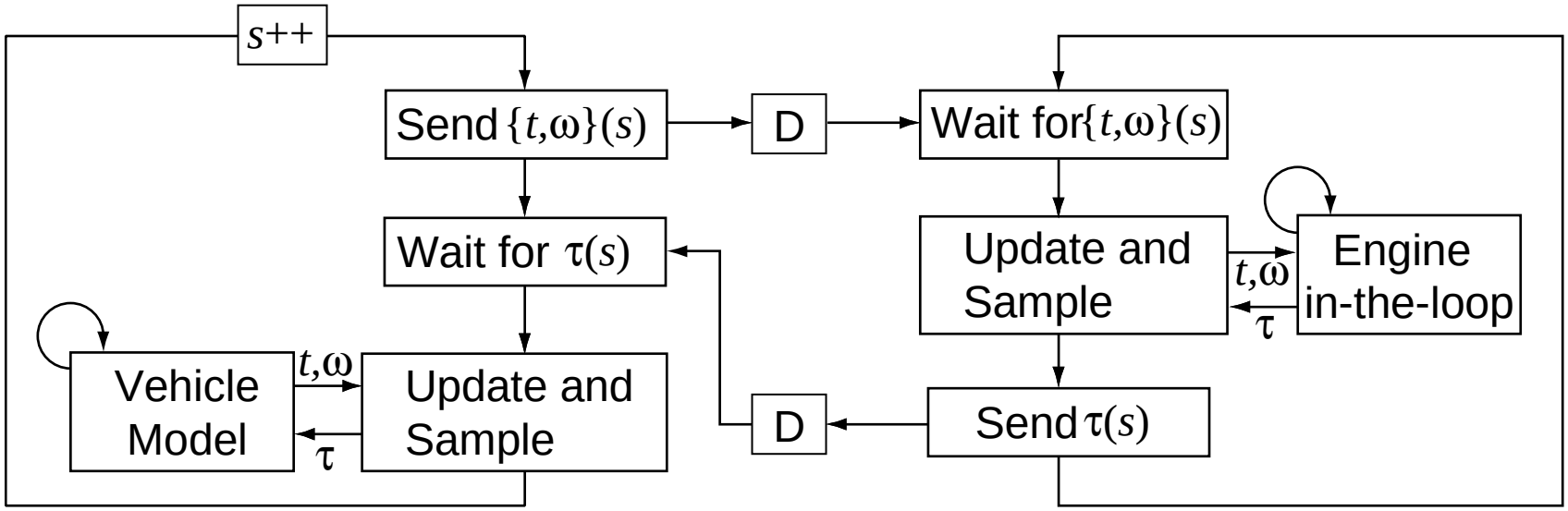
τ



UofM

Description: Approach

- Each lab executes its respective real-time thread
  - Real-time thread executes in the time domain, *t*
  - Non-blocking communications initiate events in the sample domain, *s*
- Do not allow data to accumulate in queue.
- Events are driven by sending and arrival of packets.
- Each update has a limited effect with regard to time.

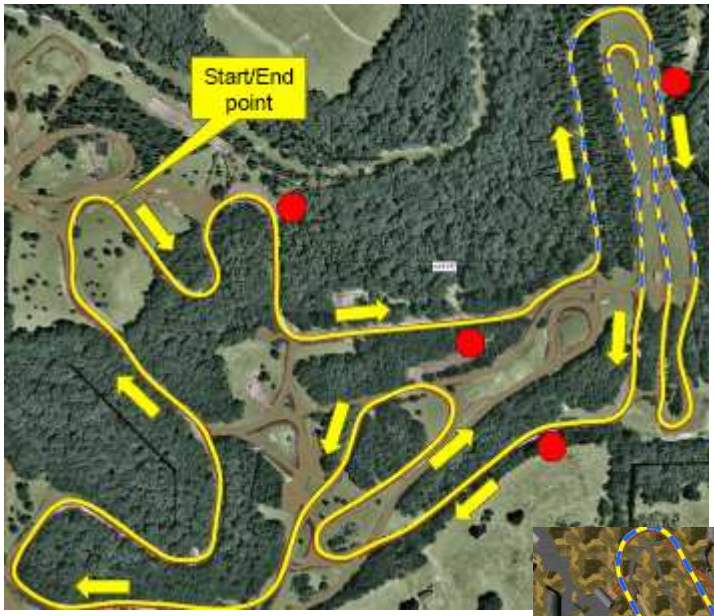


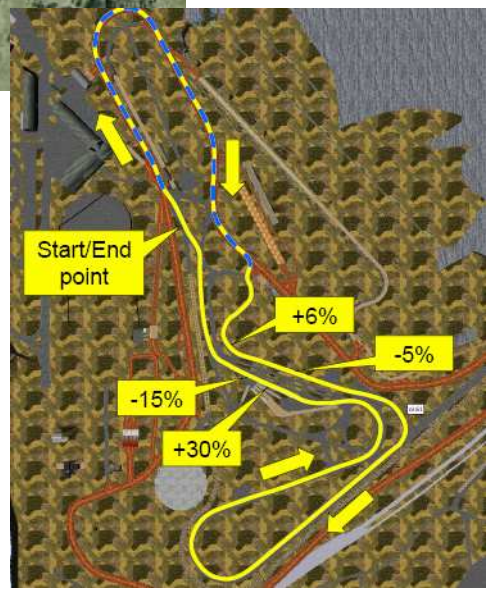
Description: Development plan

- Model-based internet integration with the actual engine
  - Preview added to driver model
- Replace internet model with LAN
- Replace LAN with internet
- Replace VESIM vehicle with TARDEC vehicle
  - Increased transmission damping ($\zeta \approx 0.014$)
  - Scaled engine by 50%
  - Redesigned driveline
  - Increased delay (up to 5x)
- Bring in the Motion Simulator

Description: Experiment

- 4 different drivers
- 2 different delay conditions
  - 25 ms
  - 125 ms
- 2 different closed courses at Aberdeen
  - Munson SFC
  - Churchville B





Results: Internet Delay Benchmark